1

PM-1 3½"x4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT

PRECISIONSM RESOLUTION TARGETS

National Library
of Canada

Acquisitions and
Bibliographic Services Branch

395 Wellington Street
Ottawa, Ontario
K1A 0N4

Bibliothèque nationale
du Canada

Direction des acquisitions et
des services bibliographiques

395, rue Wellington
Ottawa (Ontario)
K1A 0N4

Your file Votre référence

Our file Notre référence

NOTICE

The quality of this microform is heavily dependent upon the quality of the original thesis submitted for microfilming. Every effort has been made to ensure the highest quality of reproduction possible.

If pages are missing, contact the university which granted the degree.

Some pages may have indistinct print especially if the original pages were typed with a poor typewriter ribbon or if the university sent us an inferior photocopy.

Reproduction in full or in part of this microform is governed by the Canadian Copyright Act, R.S.C. 1970, c. C-30, and subsequent amendments.

AVIS

La qualité de cette microforme dépend grandement de la qualité de la thèse soumise au microfilmage. Nous avons tout fait pour assurer une qualité supérieure de reproduction.

S'il manque des pages, veuillez communiquer avec l'université qui a conféré le grade.

La qualité d'impression de certaines pages peut laisser à désirer, surtout si les pages originales ont été dactylographiées à l'aide d'un ruban usé ou si l'université nous a fait parvenir une photocopie de qualité inférieure.

La reproduction, même partielle, de cette microforme est soumise à la Loi canadienne sur le droit d'auteur, SRC 1970, c. C-30, et ses amendements subséquents.

Canada

AICTIN

ANALYTICAL IMPROVEMENT OF CONTOUR BASED TRIANGULATED IRREGULAR NETWORK

FOR GEOGRAPHICAL INFORMATION SYSTEMS

By Zhenwu Wang

**A thesis submitted to
The faculty of Graduate Studies and Research
in partial fulfillment for the degree of**

Master of Arts

Department of Geography

**Carleton University
Ottawa, Ontario
September, 1, 1994
© copyright
1994, Zhenwu Wang**

National Library
of Canada

Acquisitions and
Bibliographic Services Branch

395 Wellington Street
Ottawa, Ontario
K1A 0N4

Bibliothèque nationale
du Canada

Direction des acquisitions et
des services bibliographiques

395, rue Wellington
Ottawa (Ontario)
K1A 0N4

Your file Votre référence

Our file Notre référence

**THE AUTHOR HAS GRANTED AN
IRREVOCABLE NON-EXCLUSIVE
LICENCE ALLOWING THE NATIONAL
LIBRARY OF CANADA TO
REPRODUCE, LOAN, DISTRIBUTE OR
SELL COPIES OF HIS/HER THESIS BY
ANY MEANS AND IN ANY FORM OR
FORMAT, MAKING THIS THESIS
AVAILABLE TO INTERESTED
PERSONS.**

**L'AUTEUR A ACCORDE UNE LICENCE
IRREVOCABLE ET NON EXCLUSIVE
PERMETTANT A LA BIBLIOTHEQUE
NATIONALE DU CANADA DE
REPRODUIRE, PRETER, DISTRIBUER
OU VENDRE DES COPIES DE SA
THESE DE QUELQUE MANIERE ET
SOUS QUELQUE FORME QUE CE SOIT
POUR METTRE DES EXEMPLAIRES DE
CETTE THESE A LA DISPOSITION DES
PERSONNE INTERESSEES.**

**THE AUTHOR RETAINS OWNERSHIP
OF THE COPYRIGHT IN HIS/HER
THESIS. NEITHER THE THESIS NOR
SUBSTANTIAL EXTRACTS FROM IT
MAY BE PRINTED OR OTHERWISE
REPRODUCED WITHOUT HIS/HER
PERMISSION.**

**L'AUTEUR CONSERVE LA PROPRIETE
DU DROIT D'AUTEUR QUI PROTEGE
SA THESE. NI LA THESE NI DES
EXTRAITS SUBSTANTIELS DE CELLE-
CI NE DOIVENT ETRE IMPRIMES OU
AUTREMENT REPRODUITS SANS SON
AUTORISATION.**

ISBN 0-315-98535-6

Canada

Name Zhenwu Wang

Dissertation Abstracts International is arranged by broad, general subject categories. Please select the one subject which most nearly describes the content of your dissertation. Enter the corresponding four-digit code in the spaces provided.

Geography

SUBJECT TERM

0 3 6 6

SUBJECT CODE

U·M·I

Subject Categories

THE HUMANITIES AND SOCIAL SCIENCES

COMMUNICATIONS AND THE ARTS

Architecture 0729
Art History 0377
Cinema 0900
Dance 0378
Fine Arts 0357
Information Science 0723
Journalism 0391
Library Science 0399
Mass Communications 0708
Music 0413
Speech Communication 0459
Theater 0465

EDUCATION

General 0515
Administration 0514
Adult and Continuing 0516
Agricultural 0517
Art 0273
Bilingual and Multicultural 0282
Business 0688
Community College 0275
Curriculum and Instruction 0727
Early Childhood 0518
Elementary 0524
Finance 0277
Guidance and Counseling 0519
Health 0680
Higher 0745
History of 0520
Home Economics 0278
Industrial 0521
Language and Literature 0279
Mathematics 0280
Music 0522
Philosophy of 0998
Physical 0523

Psychology 0525
Reading 0535
Religious 0527
Sciences 0714
Secondary 0533
Social Sciences 0534
Sociology of 0320
Special 0529
Teacher Training 0530
Technology 0710
Tests and Measurements 0288
Vocational 0747

LANGUAGE, LITERATURE AND LINGUISTICS

Language 0679
General 0289
Ancient 0290
Linguistics 0291
Modern 0401
Literature 0294
General 0295
Classical 0297
Comparative 0298
Medieval 0316
Modern 0591
African 0305
American 0352
Asian 0355
Canadian (English) 0593
Canadian (French) 0311
English 0312
Germanic 0315
Latin American 0313
Middle Eastern 0314
Romance 0370
Slavic and East European 0372

PHILOSOPHY, RELIGION AND THEOLOGY

Philosophy 0422
Religion 0318
General 0321
Biblical Studies 0319
Clergy 0320
History of 0322
Philosophy of 0469
Theology 0323

SOCIAL SCIENCES

American Studies 0324
Anthropology 0326
Archaeology 0327
Cultural 0310
Physical 0272
Business Administration 0770
General 0454
Accounting 0338
Banking 0385
Management 0501
Marketing 0503
Canadian Studies 0505
Economics 0508
General 0509
Agricultural 0510
Commerce-Business 0511
Finance 0358
History 0366
Labor 0351
Theory 0358
Folklore 0366
Geography 0351
Gerontology 0578
History 0578

Ancient 0579
Medieval 0581
Modern 0582
Black 0328
African 0331
Asia, Australia and Oceania 0332
Canadian 0334
European 0335
Latin American 0336
Middle Eastern 0333
United States 0337
History of Science 0585
Law 0398
Political Science 0615
General 0616
International Law and Relations 0617
Public Administration 0814
Recreation 0452
Social Work 0626
Sociology 0627
General 0938
Criminology and Penology 0631
Demography 0628
Ethnic and Racial Studies 0629
Individual and Family Studies 0630
Industrial and Labor Relations 0700
Public and Social Welfare 0344
Social Structure and Development 0709
Theory and Methods 0999
Transportation 0453
Urban and Regional Planning 0453
Women's Studies 0453

THE SCIENCES AND ENGINEERING

BIOLOGICAL SCIENCES

Agriculture 0473
General 0285
Agronomy 0475
Animal Culture and Nutrition 0476
Animal Pathology 0359
Food Science and Technology 0478
Forestry and Wildlife 0479
Plant Culture 0480
Plant Pathology 0817
Plant Physiology 0777
Range Management 0746
Wood Technology 0306

BIOLOGY

General 0287
Anatomy 0308
Biostatistics 0309
Botany 0379
Cell 0329
Ecology 0353
Entomology 0369
Genetics 0793
Limnology 0410
Microbiology 0307
Molecular 0317
Neuroscience 0416
Oceanography 0433
Physiology 0821
Radiation 0778
Veterinary Science 0472
Zoology 0786
Biophysics 0760
General 0425
Medical 0993

EARTH SCIENCES

Biogeochemistry 0425
Geochemistry 0993

Geodesy 0370
Geology 0372
Geophysics 0373
Hydrology 0388
Mineralogy 0411
Paleobotany 0345
Paleocology 0426
Paleontology 0418
Paleozoology 0985
Palynology 0427
Physical Geography 0368
Physical Oceanography 0415

HEALTH AND ENVIRONMENTAL SCIENCES

Environmental Sciences 0768
Health Sciences 0566
General 0300
Audiology 0992
Chemotherapy 0567
Dentistry 0350
Education 0769
Hospital Management 0758
Human Development 0982
Immunology 0564
Medicine and Surgery 0347
Mental Health 0569
Nursing 0570
Nutrition 0380
Obstetrics and Gynecology 0354
Occupational Health and Therapy 0381
Ophthalmology 0571
Pathology 0419
Pharmacology 0572
Pharmacy 0382
Physical Therapy 0573
Public Health 0574
Radiology 0575
Recreation 0460

Speech Pathology 0460
Toxicology 0383
Home Economics 0386

PHYSICAL SCIENCES

Pure Sciences 0485
Chemistry 0749
General 0486
Agricultural 0487
Analytical 0488
Biochemistry 0738
Inorganic 0490
Nuclear 0491
Organic 0494
Pharmaceutical 0495
Physical 0754
Polymer 0405
Radiation 0605
Mathematics 0986
Physics 0606
General 0608
Acoustics 0748
Astronomy and Astrophysics 0607
Atmospheric Science 0798
Atomic 0759
Electronics and Electricity 0609
Elementary Particles and High Energy 0610
Fluid and Plasma 0752
Molecular 0756
Nuclear 0611
Optics 0463
Radiation 0346
Solid State 0984
Statistics 0346
Applied Sciences 0984
Computer Science 0346

Engineering 0537
General 0538
Aerospace 0539
Agricultural 0540
Automotive 0541
Biomedical 0542
Chemical 0543
Civil 0544
Electronics and Electrical 0348
Heat and Thermodynamics 0545
Hydraulic 0546
Industrial 0547
Marine 0794
Materials Science 0548
Mechanical 0743
Metallurgy 0551
Mining 0552
Nuclear 0549
Packaging 0765
Petroleum 0554
Sanitary and Municipal 0790
System Science 0428
Geotechnology 0796
Operations Research 0795
Plastics Technology 0994
Textile Technology 0994

PSYCHOLOGY

General 0621
Behavioral 0384
Behavioral 0622
Clinical 0620
Developmental 0623
Experimental 0624
Industrial 0625
Personality 0989
Physiological 0349
Psychobiology 0632
Psychometrics 0451
Social 0451

**The undersigned recommend to the Faculty of Graduate Studies
and Research acceptance of the thesis**

AICTIN

**ANALYTICAL IMPROVEMENT FOR CONTOUR BASED
TRIANGULATED IRREGULAR NETWORK**

FOR GEOGRAPHICAL INFORMATION SYSTEMS

**Submitted by Zhenwu Wang
in partial fulfillment of the requirements for
the degree of Master of Arts**

Thesis Supervisor

Chair, Department of Geography

Carleton University

Sept. 1, 1994

ABSTRACT

The research focused on the development of an Analytical Improvement for Contour based Triangulated Irregular Network (AICTIN) used in the creation of Digital Elevation Models (DEM) of landscape. The objectives of the project are to analyze and summarize the relationship between relief, contour lines and contour based TIN, in order to automatically detect and solve the main problems occurring in contour based TIN. The research was primarily concentrated in three steps: conceptual design, algorithm design, and implementation and testing. In conceptual design, the basic topographic elements -- slopes, valleys, ridges, peaks, pits and saddles -- are abstracted from the topographical to the topological sense, the relations of each element to its associated contour lines and triangles are analyzed, and the problem triangles are classified into groups of which each has specific relations with the associated contour lines and locations in the elements. In the algorithm design stage, the algorithm of processing each group of problem triangles is discussed, and the processing sequence for different groups is analyzed. The implementation of AICTIN is introduced. And the result of tests with real contour line data and the performance of AICTIN are analyzed. Finally, the conclusion of the research and the suggestions for the further development are proposed. AICTIN is shown to be significant advantages over existing methods of creating TIN.

ACKNOWLEDGMENT

I would first like to express my appreciation to my supervisor, Dr. D. R. F. Taylor, for his advice, support and encouragement throughout the M. A. program.

The research was carried out with research funds provided to the Geomatics and Cartographic Research Unit of Carleton University by Intera TYDAC Technologies Inc. I wish to thank TYDAC and the Unit for providing the funds and all the facilities on the research. Grateful thanks go to Dr. G. Zeiss, the former vice president of TYDAC, and the adjunct advisor of the M. A. program, for his guidance to the research topic, encouragement and careful review on the proposed approach of the research work.

I also want to acknowledge Dr. M. Fox, Dr. I. Wallace, and Ms. H. Anderson, for their support and help during the M. A. program.

Special thanks go to my friend David R. Campanas, for his English proof-reading of the manuscript of the thesis.

I wish to thank all my friends in Ottawa, especially, Shabai, Aining, and Jing, for their helps and friendship.

My grateful thanks extend to my daughter, Qian, for her tolerance and understanding during the thesis writing.

Last, I want to express my appreciation to my wife, Jun, for her constructive criticism on some chapters of the thesis, and all the support I got from her.

TABLE OF CONTENTS

ACCEPTANCE SHEET	ii
ABSTRACT.....	iii
ACKNOWLEDGMENTS	iv
TABLE OF CONTENTS	v
LIST OF FIGURES	ix
1 INTRODUCTION	1
1.1 Background	1
1.2 Areas of Study	3
1.3 Objectives of the Project.....	4
1.4 Proposed Methodology	4
1.5 Organization of the Thesis and Presentation.....	5
2 LANDFORMS AND THEIR REPRESENTATION.....	7
2.1 Introduction	7
2.2 Landforms.....	7
2.2.1 Application of Landform Information.....	7
2.2.2 Representation of Landform Information	9
2.3 Digital Elevation Models (DEMs)	11
2.3.1 Analysis on Two DEM Structures, Grid and TIN.....	11
2.3.1.1 Rectangular Grid.....	11

2.3.1.2 Triangulated Irregular Network (TIN)	15
2.3.2 A Comparison between Grid and TIN	17
2.3.3 Problems Occurring in Contour Based TIN	17
2.3.3.1 Triangle Crossing Contour Lines	18
2.3.3.2 Spurious Horizontal Triangles	19
2.4 Summary	20
3 CONCEPTUAL DESIGN OF AICTIN.....	21
3.1 Introduction	21
3.2 Current Development on Improvement of Contour Based TIN	21
3.2.1 L. Scarlatos' method.	21
3.2.2 A. Christensen's method.....	25
3.2.3 M. Brändli's method.....	27
3.3 Conceptual Design of AICTIN	31
3.3.1 Improvement based on Delaunay Triangulation	32
3.3.2 Relationships between Relief, Contour Lines and a Contour based TIN.....	33
3.3.3 Detection of Problem Triangles.....	37
3.3.4 Splitting Problem Triangles by Inserting Supplementary Points	39
3.3.5 Elevation Interpolation for the Inserted Points	40
3.4 Summary	41

4 ALGORITHM DESIGN FOR AICTIN	42
4.1 Introduction	42
4.2 Splitting Triangles Crossing Contour Lines.....	42
4.3 Splitting Spurious Horizontal Triangles	44
4.3.1 Non-Contour-Segment Triangles	44
4.3.2 Two-Contour-Segment Triangles.....	45
4.3.3 One-Contour-Segment Triangles.....	46
4.3.4 Full-Contour-Segment Triangles	47
4.3.5 Processing Sequence for Splitting Spurious Horizontal Triangles	47
4.4 Elevation Interpolation for Inserted Points.....	50
4.4.1 Elevation Interpolation for Valleys and Ridges.....	50
4.4.1.1 Elevation Interpolation for Valleys	53
4.4.1.2 Elevation Interpolation for Ridges	56
4.4.2 Elevation Interpolation for Peaks, Pits and Saddles	56
4.5 The Relationship with Scattered Elevation Points	60
4.6 Summary.....	60
5 IMPLEMENTATION AND DATA TESTING	62
5.1 Introduction	62
5.2 Implementation	62
5.2.1 Abstracting Elevation Points from Contour Lines.....	62

5.2.2 Generating Delaunay Triangulation	63
5.2.2.1 A Brief Overview of Delaunay Triangulation Algorithms	64
5.2.2.2 The Triangulating Algorithm Used in The Project.....	69
5.2.3 Solving the Two Problems in Contour based TIN	72
5.2.3.1 Splitting of The Non-Contour-Edge Horizontal Triangles.....	72
5.2.3.2 Splitting Other Spurious Horizontal Triangles	75
5.2.3.3 Abstracting A Break Line Network from The Triangulation	76
5.2.3.4 Determination of The Valley Path Interpolation Unit	78
5.3 Data Testing.....	81
5.4 Summary.....	82
6 CONCLUSION.....	83
6.1 Summary and Conclusion.....	83
6.2 Suggestions for Further Development	86
BIBLIOGRAPHY	88

LIST OF FIGURES

Figure 2.1 Contour vertices and elevation points fall between grid points.....	13
Figure 2.2 Two possibilities in conversion from grid to TIN	14
Figure 2.3 Different combinations of triangles represent different surfaces.....	14
Figure 2.4 Two possibilities of conversion from grid to contour lines.....	15
Figure 2.5 Contour segment is crossed by triangles	17
Figure 2.6 Spurious horizontal triangles	20
Figure 3.1 Scarlatos' method	22
Figure 3.2 Determine the slope at A with contour lines	23
Figure 3.3 Triangles vary with the direction of contour lines	24
Figure 3.4 "Medial axes" of Christensen's method	25
Figure 3.5 Different precisions between contour lines and the medial axes.....	26
Figure 3.6 Some horizontal triangles cannot be eliminated with lower precision medial axes	27
Figure 3.7 Problem of triangle crossing contour line is solved by relaxing Delaunay criterion.....	28
Figure 3.8 Examples of horizontal triangles which can also be eliminated by relaxing Delaunay criterion.....	28
Figure 3.9 Examples of horizontal triangles which cannot be eliminated by relaxing Delaunay criterion.....	29
Figure 3.10 Horizontal triangles in a crooked valley are eliminated by inserting points....	29
Figure 3.11 Valleys intersect together in hilly areas.....	31
Figure 3.12 Links between non-contour-segment edges are similar to the medial axes in Christensen's method	33
Figure 3.13 Contour lines are interrupted originally on the maps	34

Figure 3.14 Some triangles crossing contour lines have normal elevations on their vertices.....	36
Figure 3.15 Spurious horizontal triangles	38
Figure 3.16 Elevation interpolation along break lines	41
Figure 4.1 The triangles crossing the contour line are detected sequentially	42
Figure 4.2 The edges and the associated triangles are split sequentially	43
Figure 4.3 Some horizontal triangles are created after splitting triangles crossing contour lines	44
Figure 4.4 Splitting non-contour-segment triangles	45
Figure 4.5 Splitting a two-contour-segment triangle	46
Figure 4.6 Splitting an one-contour-segment triangle	46
Figure 4.7 Splitting a full-contour-segment triangle.....	47
Figure 4.8 Triangle A has four edges after the neighboring triangle is split	47
Figure 4.9 Variation of the number of the triangle vertices	48
Figure 4.10 Splitting the non-contour-segment triangle into three triangles, if the circumcenter is inside the triangle.....	49
Figure 4.11 Splitting the non-contour-segment triangle into two triangles as well as the neighboring triangle, if the circumcenter is outside the triangle	49
Figure 4.12 Break lines intersect together in one unit	51
Figure 4.13 Example of a) There are two paths from A to D; b) Many paths pass by point C	52
Figure 4.14 A slope error occurs with the elevation averaged by different paths.....	54
Figure 4.15 Interpolation unit of a peak and a saddle.....	56
Figure 4.16 Extreme elevation point in the interpolation unit of a peak	57
Figure 4.17 Extreme elevation point in the interpolation unit of a saddle	57

Figure 4.18 Non-linear elevation interpolation for the points on the outline of the triangulation	58
Figure 4.19 The elevation at point A is difficult to non-linearly interpolate before the surrounding valley unit is interpolated	59
Figure 4.20 After the elevation on point C is non-linearly interpolated, the break line AB has been separated into AC and BC	60
Figure 5.1 Swap of triangle edge	64
Figure 5.2 The circumcircles of the two triangles before and after the swap.....	64
Figure 5.3 A "divide and conquer" algorithm of triangulation	66
Figure 5.4 Time consuming variation of N^2 and $N\log N$ algorithm with increasing of N	67
Figure 5.5 Operation flow of the "divide and conquer" triangulation.....	68
Figure 5.6 The points to be linked to the subsequent point can be determined by the outline of the triangulation from the previous point	69
Figure 5.7 Triangulation algorithm used in the project	71
Figure 5.8 Comparison of insertion and removal operation between two data structures: array and linked list.....	73
Figure 5.9 Special case for two non-contour-segment triangles which share the same substitute of the circumcenters	74
Figure 5.10 Processing sequence of non-contour-segment triangles whose circumcenters are outside	75
Figure 5.11 Eliminating horizontal triangles "edge by edge"	75
Figure 5.12 A small saddle without horizontal triangle	76
Figure 5.13 An interpolation unit and its representation in a two dimensional array	78
Figure 5.14 Valley path searches: recursive (upper) and non-recursive (lower)	80

1 INTRODUCTION

1.1 Background

Landform is one of the important factors which influence the social-economic activities of the society. In order to understand, study and utilize different landforms, a graphical representation is often required. Landform and its representation, therefore, have been a research domain in geography and cartography. The cartographic representation of landforms has experienced several significant stages from pictorial symbols, to hachuring, to contour lines. Because contour lines can represent the landforms more accurately than the others, they have dominated the landform representation on topographic maps since they were introduced into cartography in 19th century (Zhu and Yin, 1982).

With the rapid development of computer science and information technology, Geographical Information Systems (GIS) provide powerful tools to collect, manipulate, analyze and represent geographically related information. GIS also provides the capability of representing a portion of the earth's surface through a digitally simulated surface, otherwise known as Digital Elevation Model (DEM). With DEM, the computations, analyses, and representations which are difficult by conventional methods, can be carried out easily. The two most commonly used structures in DEMs are rectangular Grid and Triangulated Irregular Network (TIN) (Weibel and Heller, 1991).

Grid and TIN both have advantages and disadvantages, but TIN has been becoming increasingly popular in GIS products because: 1) "TIN can use fewer points, capture the critical points that define discontinuities like ridge crests, and can be topologically encoded so that adjacency analyses are more easily done" (Aronoff., 1991: 122); 2) TIN has higher

precision, due to the fact that the elevation points are often original, rather than interpolated; and 3) TIN can be converted into other structures, like Grid or contour lines with no ambiguities. To use the TIN structure, however, it is optimal to have so called "very important points -- VIPs" (VIPs are topographically significant points which represent the slope varying locations on the earth surface, and the points inserted in the TIN for ensuring the relief is correctly represented). However, the collection of those points normally requires expensive equipment and experienced operators. In practice, therefore, the vertices of contour lines and scattered elevation points digitized from existing maps are often used. The TIN constructed in this method can be called "contour based TIN". Because the vertices from contour lines are not all VIPs, two types of problems can occur here. First, the contour lines may be crossed by triangles, so that the slope here will be mis-represented. Second, the three vertices of one triangle may have the same elevation, forming a horizontal triangle. Both cases will result in the generation of problem triangles. The existence of the problem triangles will affect the application of the TIN, the automated conversion between the TIN and other data structures, and the quality of the products derived from the TIN.

The quality of a TIN is so important that the performance of a contour based TIN needs to be improved. Although interactive editing and topographic break lines can be used to improve it, interactive editing is time consuming, and the break line information is difficult to obtain. Therefore, there are attempts to solve the problems occurring in contour based TINs, but they are not very efficient, or are still under research (Weibel and Heller, 1991).

Based on the analysis of the current development, an attempt to improve the performance of contour based TIN prompted the research and development of AICTIN -- Analytical

Improvement for Contour based TIN. Automatic elimination of problem triangles is the aim of this project; analytical analysis on the relations between landforms, contour lines and the contour based triangulation is used to accomplish the aim.

1.2 Areas of Study

Since GIS itself is an interdisciplinary research and application field, as an important component in GIS, the research on TIN structure DEM will involve many related disciplines, which are:

Geography and Geomorphology: The landforms are important research subjects in geography and geomorphology. In the development of AICTIN, the geomorphological knowledge about the variety of landforms and their relationship with contour lines is very helpful in the concept design stage of AICTIN.

Cartography: Contour lines are a very important cartographic component to quantitatively represent the landforms. It is one of the most important premises to understand the geometrical and topological characteristics of the contour lines in various topographic areas such as valleys, ridges, peaks, pits, and saddle parts, etc. in the analysis of relations between contour lines and the contour based triangulation.

Geographical Information Systems: The understanding of the principle of GIS and the role that DEM plays in GIS is the basis of designing the DEM as appropriate as possible to the objectives of GIS and evaluating the quality of the DEM.

Computational Geometry: Computing efficiency is one of the most important criteria to evaluate algorithms. In addition, algorithms for triangulation are also discussed as one of the major research topics in computational geometry.

1.3 Objectives of the Project

The objective of the project is to find a method which can automatically detect and eliminate all problem triangles in a TIN. In order to be effective and efficient, AICTIN works in a different way from other related approaches. It starts with an analysis of the relationship between landforms, contour lines and triangles in the TIN. From the relationship analysis, all problem triangles can automatically be detected and corrected.

1.4 Proposed Methodology

Analysis of current development: The performance problem of contour based TIN has been recognized and researched for years, but few solutions have been produced. They must be studied carefully.

Conceptual design: As the first stage of the project, the conceptual design builds the basis of the project's success. A good conceptual design ought to identify the issues clearly and make the scheme feasible, complete, and decomposable for ease of implementation.

Algorithm design: Based on the conceptual design, the processing algorithms for all cases described in the conceptual design stage must be worked out in detail. Not only the theoretical, but also the practical feasibility of the algorithm should be considered. Algorithm design of the project is the key link between the conceptual design and the implementation of the project.

Implementation and testing: Because of the complexity and irregularity of landforms, any terrain information related approach can hardly be evaluated without implementation and being tested by real terrain data. In addition, the implementation also provides an

opportunity to verify the optimization of the algorithms designed in the algorithm design stage.

1.5 Organization of the Thesis and Presentation

The research involved two major components: the theoretical basis of AICTIN and its implementation as part of an operational GIS.

AICTIN is a complete DEM system. It includes abstracting elevation sample points from digital contour lines, generating triangulation, detecting problem triangles, resolving the problem triangles by inserting supplementary points, and interpolating elevations for the inserted points. AICTIN was developed with the C programming language in OS/2 environment on IBM compatible PCs. After a number of tests with different data sets, the system met the objectives established in the project design.*

The thesis describes the research component for this project in six chapters. Chapter one is the introduction to the project explaining the reasons why this project has been undertaken, the purpose of the project, the objectives to be realized, and the methods for achieving these objectives. The next chapter discusses landforms and their representation in analog and digital form, analyzes the advantages and disadvantages of TIN applied to represent landforms in GIS, and the problems that occur in a contour based TIN. After a detailed analysis on the current development in this specific field, chapter 3 deals with the conceptual design for AICTIN, and introduces the analytical approach for improvement applied in the project. Based on the conceptual design, chapter 4 focuses

* AICTIN is scheduled to be used in the new version of SPANS MAP, a GIS product of TYDAC.

on the method and algorithm design for each case discussed in the conceptual design stage. Chapter 5 discusses some practical issues encountered during implementation, the efforts for improving the efficiency of the algorithms, and the analysis of the data test results. The last chapter presents the conclusions of the project and discusses further development in the field of contour based TIN.

2 LANDFORMS AND THEIR REPRESENTATION

2.1 Introduction

"Landforms are closely and intricately related to man's use and occupation of the land" (Kendall, 1951: 178). To understand landform is essential for the planning of social activities, while landform representation is a major basis for landform study. This chapter will give a brief overview of the landform and its representation, especially the digital elevation models.

2.2 Landforms

According to Kendall, "... the top of the earth's crust possesses an amazing variety of forms. It has been wrinkled, warped, broken, and worn into many shapes. Such shapes are landforms whether they be small or large, simple or complex" (Kendall, 1951: 178). Landform greatly influences people's habitation, production, transportation. These influences can be direct; such as transportation difficulties in mountain area, or indirect; such as the influence of landforms upon the weather in a specific region. Muehrcke states "... the terrain surface provides the foundation upon or near which our lives are played out. Nothing in the environment appears to be immune to landform influences. Human orientation, mobility, and environmental understanding are all affected in one way or another by the terrain surface" (Muehrcke, 1986: 127).

2.2.1 Application of Landform Information

Since landforms influence much of human life, they should be understood and studied, in order "...to assist in the efficient discovery, assessment and wise management of the earth's

finite resources, to prevent environmental deterioration and to avoid or prevent natural hazards" (Brunsden, 1985: 225). In general, landforms are mainly considered by the following domains:

Surveying and mapping: These domains deal primarily with the collection and representation of landform information, as well as the provision of landform representation products used by related domains. Meanwhile, the landform information is also applied in the domains themselves to produce orthorectified air-photos and satellite images.

Civil engineering: The landform is an important elements to be considered in site (or route) planning in civil engineering. For example, it is important in planning an airport to consider the elevations on the surrounding areas, especially in mountainous areas. Slope is crucial for route planning, and visibility is significant for the location of a radar station. A characteristic of application in civil engineering is that the concerned area of landforms is relatively smaller than those in other application domains.

Planning and resource management: Planning and resource management is a major domain of landform information use. This domain includes environmental and urban planning, remote sensing, soil science, agriculture, forestry, meteorology and climatology. Typical applications are the study of environmental impact, industrial site location; the geometric and radiometric correction of remote sensing images; support of image classification in remote sensing; estimation of soil erosion potential; study of crop suitability; development of harvesting strategies; wind flow and pollution dispersion analysis; and so on.

Earth sciences: The uses of landform information in the earth sciences are mostly distributed in geology, geomorphology, hydrology and glaciology. Besides the many

similarities with other applications in natural resources management, they require specific functions for modeling and interpretation of terrain discontinuities, such as drainage and divide network.

Military applications: Military applications contain the applications in all other domains. Terrain is one of the most important components of the military environment at the local or regional scale. Military uses of landform information including site planning operations similar to those in civil engineering. "Terrain analysis for battlefield management involves tasks such as intervisibility and vehicle trafficability analysis. Missile guidance and planning of communication networks are other typical military uses of landform information" (Weibel and Heller, 1991: 293).

2.2.2 Representation of Landform Information

As a complex variety of the earth surface, landforms are not only difficult to describe in a literal manner, but also difficult to represent on a planar medium like a map. Birch states that "most features are readily shown on maps either by drawing them to scale or arbitrarily out of scale, by characteristic drawing, or by conventional signs. Relief offers a peculiar problem because it involves the third dimension" (Birch, 1949: 82). However, because of the necessity of understanding and studying landforms in all application domains, the representation of landforms has been an important research topic in surveying and mapping for centuries. With the development of the theory and technology of surveying and mapping, there have been several methods developed for the representation of landforms. The three main representative methods are pictorial symbols, hachures, and contour lines. Finch gives the criteria to evaluate the representative methods of landforms, that "the method adapted to show the relief must indicate clearly three things: 1, the shape and size of the hills; 2, the slope; and 3, the height of the

ground" (Finch, 1920: 18). Since the hachuring method was introduced, pictorial symbols have been seldom used on topographic maps, because of their inability to satisfy the three conditions. "Hachuring method is a method of hill shading by closely set parallel lines" (Raisz, 1948: 124). Hachures can vividly represent the shape, size and slope of hills and mountains, but do not indicate height values. With the development of science and technology, the height values of the landforms have been becoming increasingly important for various domains. Thus, a more precise method, the contour line method, has been used in the surveying and mapping domain, and by far the most common method to represent the landforms, especially on topographic maps. "A contour line is one on which all points are of equal vertical distance above or below a datum" (Lawrence, 1979: 18). From a contour map, all of the important values, such as heights, shapes, sizes and slopes of the hills or mountains can be directly or indirectly represented. The disadvantage of the contouring method is that the three dimensional image of the hills can only be discovered by experienced map users.

With the emergence and development of computer technique and information theory, the representation of landform information has also entered a new stage. Digital Elevation Models (DEMs), as a set of elevation values with a special structure stored in computer based Geographical Information Systems (GIS), can provide not only accurate values of landform information, such as heights, slopes, aspects, profiles, but also pictorial displays like hill shadings and perspective images. In addition, combined with the abundant calculating and analyzing functions in GIS, DEMs play an important role in the application domains. About one-third of all applications in these domains make use of DEMs or derived products at some point (Weibel and Heller, 1991).

2.3 Digital Elevation Models (DEMs)

A digital elevation model can be understood as a digital representation of a portion of the earth's surface. The "digital elevation data are a set of elevation measurements for locations distributed over the land surface" (Aronoff, 1991: 121). The most commonly used data structures in DEMs are rectangular Grid and TIN (Triangulated Irregular Network). Rectangular Grid structures represent the terrain information with a grid format in which an elevation value is stored for each of a set of regularly spaced ground positions. "The TIN structures, on the other hand, are based on triangular elements, with vertices at the elevation sample points" (Weibel and Heller, 1991: 273). Because TIN structures can use many fewer points than grid structures to represent the landforms with comparable accuracy together with many other advantages, TIN has been becoming increasingly popular in recent years.

2.3.1 Analysis on Two DEM Structures, Grid and TIN

Of the two most commonly used structures for DEMs, each has its own advantages and disadvantages. An analysis is made of the two structures in the following aspects: 1) storage space; 2) construction and manipulation; 3) accuracy of representing landforms; and 4) conversion to other structures.

2.3.1.1 Rectangular Grid

Storage Space

The storage space for a Grid depends on the point density of the Grid. The higher density of points a Grid has, the more precisely relief can be represented. However, if the point density of a Grid is doubled in the X and Y direction, the storage space will be increased

four times, meanwhile, the processing speed will also be reduced by four times. Therefore, in many GIS projects, to determine the point density of the Grid in GIS project is a difficult task, and often ends up with a compromise between the point density, the storage space, and the processing speed requirements.

Another difficulty of determining the point density of Grid is the variety of the terrain in one study area. Although a Grid with higher point density can represent relief more precisely, a Grid with high point density is not always necessary, especially for representing a plain, because many grid points may have the same elevation value as their neighbors. However, a Grid with low point density also cannot be used unless there are no other landforms in the area, such as hills, mountains, etc. Otherwise, these landforms will be poorly represented with the low point density. In order to get an acceptable representation for the other landforms, a higher point density must be used and large amount of storage space must be wasted in the flatland area.

Construction and Manipulation

The process of constructing a Grid is a procedure of interpolation, because only a few grid points may fortuitously be located on the elevation sample points or contour lines. Although there are many methods for interpolation of Grids directly from elevation sample points or contour lines, some of the more widely used interpolation procedure are based on triangulation (Weibel and Heller, 1991). Obviously, it is an important, and widely used, method to construct a Grid from a TIN.

From the perspective of computer technology, a Grid can be considered as a two-dimensional array. The algorithms to manipulate a two-dimensional array are normally simple, because the spatial relationship between array elements, or grid points, is implicit. For each grid point, the surrounding points can easily be obtained without any calculation.

Accuracy

Because the elevation points of a Grid are distributed regularly, the locations corresponding to extreme elevation values, such as peaks and pits, most probably will fall between the grid points (figure 2.1), so that the interpolated elevation values on the surrounding grid points must be lower or higher than the peaks or pits, i.e. a grid structured DEM can hardly represent the extreme elevation values of the study area.

Figure 2.1 Contour vertices and elevation points fall between grid points.

Therefore, the locations and elevations of the extreme points represented in Grid will not be accurate. For example, if the highest peak in an area is 1000 meters above sea level, the maximum elevation value of the Grid in the same area will probably be less than 1000 meters and located somewhere else, unless the peak fortuitously coincides with a grid point. The same conclusion can also be applied on all tops of hills, bottoms of pits, and all other discontinuities of the earth surface.

Conversion to Other Structure:

In a Grid, since its small rectangles defined by the four adjacent grid points normally does not determine a plane, some uncertainties exist in converting it into a TIN or contour lines. It is clear that three points can form a triangle which defines a plane, and four points can

form two triangles which defines two planes. But, the four grid points ABCD can form the two triangles like ABC and BCD, or ABD and ACD (figure 2.2). Applied in Grid, the

Figure 2.2 Two possibilities in conversion from grid to TIN.

different combination can lead to different representations of the same surface (figure 2.3). When there is a small rectangle formed by four adjacent grid points whose elevation values are distributed in the way that two diagonal points are higher than a certain contour line value, e.g. 100 meters, but the other two are lower than that value, it will be difficult to

Figure 2.3 Different combinations of triangles represent different surfaces.

determine whether this rectangle represents a ridge, a valley, or a saddle, and thereby it is also difficult to determine the trend direction of that 100 meter contour line while converting the Grid into contour lines. A mis-traced contour line may not be serious in a ridge or saddle area, but it will be serious in a valley area, because the contour lines shown in figure 2.4 do not logically represent a valley (figure 2.4).

Figure 2.4 Two possibilities of conversion from grid to contour lines.

2.3.1.2 Triangulated Irregular Network (TIN)

Storage Space

It is a major advantage of a TIN that fewer points are needed here than in Grid to get comparable accuracy. Since TIN uses triangles to represent area of constant slope, a single triangle can represent a very large flat area. Therefore, using TIN to represent landform information, the minimum number of points is required. Although some storage spaces must be used to record the topological relationship between the points, the links of point pairs, and the triangles, a TIN structure is still efficient in saving storage space because the number of points required by a TIN is much less than the number of points in a Grid as outlined in detail by Weibel and Heller (1991). Poicker states that "most of the DTM's which use the irregular triangular network beyond the input stage use some type of surface-specific points as part of their data base, i.e. points which mark specific changes in the relief as peaks, passes, ridges, channels, etc. These points show up in a regular grid only if the grid is very dense. To obtain the same accuracy for the computation of different geomorphometric parameters, one needs fourteen regular points for every irregular one. However, to make sure that no structural line is misrepresented, the ratio has to be much higher" (Poicker, 1978).

Construction and Manipulation

To generate triangulation is the most complicated procedure in the construction of a TIN. The triangulation commonly used in TIN is called *Delaunay Triangulation*. A triangulation is a Delaunay triangulation "if, and only if, the circumcircle of any of its triangles does not contain any other point in its interior" (Weibel and Heller, 1991: 275). As an algorithm research topic in computational geometry, generation of a Delaunay triangulation has been well researched, and many efficient algorithms have been published. The manipulation of a TIN is more difficult than that of a Grid, because the shapes of each triangle and its relations to the surrounding triangles are irregular. For example, when a straight line is put in a Grid, the two rectangles that the two end points of the line fall in are known, and all the rectangles crossed by that line in between can easily be calculated. But, if the same line is put in a TIN, the triangle that one of the two end points falls in must be searched for in the whole triangulation, and all other triangles crossed by the line including the triangle that contains another end point, must also be calculated according to the topological relationship from the first triangle. Due to the complexity of the calculations, more effort is required to develop applications based on TIN.

Accuracy

The accuracy of a TIN is dependent on the accuracy of the elevation sample points, and whether the points are VIPs, but unlike Grid, it can properly represent the discontinuities of the relief.

Conversion to Other Structures

TIN can be converted into other structures without ambiguity, because each facet in the TIN is formed by a triangle, and the three vertices of the triangle determine a unique

plane. In the process of converting to Grid, the elevation value for each grid point can be interpolated only by the triangle that contains the grid point, if linear interpolation is used. Even for a higher order interpolation, the triangle and its neighborhoods are sufficient to calculate all of the required coefficients. The conversion to contour lines is a similar situation, because the trend directions of each contour line can be uniquely determined everywhere. "If a curve enters a triangle through one edge, it has to exit the triangle through one of the remaining two edges" (Poicker, 1978). Therefore, TIN is an appropriate intermediate structure, which can be easily converted into Grid and contour lines, when necessary.

Figure 2.5 Contour segment is crossed by triangles

2.3.2 A Comparison between Grid and TIN

Through the previous analysis on Grid and TIN, a comparison between Grid and TIN will be made below. The most important advantage of Grid is its simplicity. From the perspective of a GIS software engineer, Grid is easy to handle and the associated software is easy to develop. But, from an application point of view, Grid has the disadvantages of high storage requirements, restricted grid density, and ambiguous conversion to other structures. The TIN, alternatively, is difficult to handle and the associated software is difficult to develop. But, it can provide satisfactory accuracy with economical storage space, and convert to other structures without ambiguity. Because TIN has advantages on the application aspect, and the development of TIN and its associated software is a "one

time" investment, TIN has been increasingly selected as the "permanent" DEM structure in many sophisticated GIS products.

2.3.3 Problems Occurring in Contour Based TIN

According to the properties of TINs, a TIN will be optimal in terms of storage efficiency, if all elevation sample points are VIPs. However, to collect the VIPs requires expensive equipment and experienced staff, because a stereoscopic interpretation of aerial photographs or satellite imagery or perhaps even a field survey is required. Therefore, the individual elevation points and the vertices of contour lines digitized from topographic maps are practically used in many GIS projects. But since not all of the points are VIPs, and some VIPs are not in the point data set, two types of problems may occur in the TIN constructed from this type of data. The two types of problems will be discussed in the next two sections.

2.3.3.1 Triangle Crossing Contour Lines

According to the definitions of Delaunay triangulation, only individual points are taken as data source to generate the triangulation. The vertices of contour lines must be converted into individual elevation points beforehand. Thus, the sequential information of vertices on contour lines will not be considered during the triangulating process, but the geometric adjacency of all individual points. Therefore, it is possible that each pair of sequential vertices on the same contour line may not be linked together, if there are other points closer together on both sides of the contour line than the two sequential vertices. The contour segment formed by the two sequential vertices will be crossed by the links of those points (figure 2.5) (Christensen, 1987, Weibel and Heller, 1991).

When a triangle crosses a contour line segment, the edge of two points of the triangle, whose elevations are higher and lower than the crossed contour line, will form a constant slope. If the crossed contour line does not pass through the edge in the middle, it means that the slopes from the upper point to the contour line and from the contour line to the lower point should be different. However, the variation of slopes on both sides of the crossed contour line cannot be represented. In another word, the problem of "triangle crossing contour line" may lose the slope variation in the area.

2.3.3.2 Spurious Horizontal Triangles

Since most of the elevation points are converted from the vertices of contour lines, many points will have the same elevation value when they are originated from the same contour lines or the different contour lines with the same altitude. After the TIN is generated, the triangles, whose three vertices have the same elevation value, are called "spurious horizontal triangles". This type of triangle is distributed between two adjacent contour lines on the bottom of pits and valleys, the top of peaks and ridges, and saddles (Christensen, 1987, Weibel and Heller, 1991).

The problem of spurious horizontal triangles is more serious than the previous problem, because it influences the accuracy of the TIN so much that the appearance of the earth surface represented by the TIN would look like "terrace fields". If the TIN represents a mountainous area, the spurious horizontal triangles will be gathered in a relatively small region, because of the high density of the contour lines (figure 2.6a). But, if the represented area is a hilly area, there may be only one contour line in one valley, or one ridge, so that there may be too many horizontal triangles surrounding that contour line to represent the relief clearly (figure 2.6b). Therefore, the spurious horizontal triangle

problem should be considered as the most serious problem in constructing TIN from contour lines, and requires more effort to overcome.

a. Horizontal triangles in mountainous areas

b. Horizontal triangles in hilly areas

Figure 2.6 Spurious horizontal triangles

2.4 Summary

In this chapter, landforms and their representation have been introduced. The digital representation method, DEM, has been introduced in detail. The advantages and disadvantages of the two most commonly used DEM structures, Grid and TIN, have been analyzed and compared. The chapter ends with the discussion of the two typical problems occurring in contour based TINs. To solve the two problems is the aim of this thesis.

3 CONCEPTUAL DESIGN OF AICTIN

3.1 Introduction

The conceptual design of AICTIN is discussed in this chapter. The design is based on the analyses of several approaches often applied in this domain, and of the remaining problems. The method proposed in AICTIN is based on the properties of the triangles in the triangulation and the relationships between the triangles and the contour lines. The problem triangles will be classified into different groups. The problems, therefore, can be solved by developing a specific method for each group of triangles.

3.2 Current Development on Improvement of Contour Based TIN

The solution of the problems in contour based TIN attracts the attention of many GIS researchers, and several approaches have been developed. To study these approaches is helpful in the design of AICTIN. Three typical approaches are analyzed in this section.

3.2.1 L. Scarlatos' method.

L. Scarlatos' method is to generate a triangulation different from Delaunay triangulation. In this triangulation, the problem of "triangle crossing contour line" is avoided completely, because not only the vertices of the contour lines, but also the contour line segments are considered during triangulation. The triangulating procedure is realized in the way that each contour line is separated into sections at the extreme points on Y direction, i.e. the two sections on both sides of these points have the Y values either greater or less than the points. After that, a straight assistant line parallel to the X axis is made at each vertex of the contour lines. The assistant line expands and intersects the other two closest contour

line sections on the left and right side of the vertex. Since the contour line sections are intersected by many straight lines parallel to the X axis, the whole contour line map is transformed into a network with many small trapezoids. As determined by the way that the trapezoids are formed, the trapezoids should have the characteristics showing below:

- 1) the two hypotenuses of each trapezoid are derived from the contour line sections;
- 2) the two horizontal lines of each trapezoid are derived from the assistant lines;
- 3) in each of the trapezoids, there are at least two, and at most four, vertices which are the original vertices of the contour line sections; and
- 4) the other vertices in the trapezoid, if any, are the

A, B: Trapezoids

B: Trapezoid in which the two contour vertices are on the same side.

Figure 3.1 Scarlatos' method

intersection points between contour line sections and the assistant lines (figure 3.1).

Based on the network of the trapezoids, the triangulation can be completed in the following stages: 1) link the contour vertices along contour line sections; 2) link the contour vertices in one trapezoid from left to right; and 3) remove all assistant lines. Thus, most of the triangles can be completed. However, for linking the contour vertices between different contour sections, i.e. from left to right in one trapezoid, there are two cases which have to be specially treated. One is that when the four trapezoid vertices are all the original vertices of contour line sections, besides linking the two pairs of vertices

horizontally, only one of the diagonal vertex pairs should be linked. Otherwise, a topological mistake will occur because the triangles in this trapezoid overlap each other. The other one is that there may be only two contour vertices in one trapezoid, and distributed on the same side, i.e. they are derived from the same contour line section (trapezoid B in figure 3.1). Since these two vertices should be linked with the vertices on the other contour line section, a special process must be employed afterwards (for details, refer to Scarlatos, 1989: 146-155).

Figure 3.2 Determine the slope at A with contour lines

In Scarlatos' method, because contour lines join the triangulating procedure, and all the links between different contour lines are restricted between the pairs of adjacent contour line sections, all triangles must be formed between adjacent contour line sections. Therefore, it is guaranteed that no triangle is able to cross contour lines.

However, the triangulation constructed with Scarlatos' method has some disadvantages which may influence the quality of the TIN. Based on the assumption that the slope between two adjacent contour lines is not changed, the slope on a specific point between two contour lines is usually measured by making a straight line which passes the point and intersects the two adjacent contour lines, upper and lower. When the distance between

the two intersections is at its shortest, the slope along this straight line can be taken as the slope of that point (figure 3.2). In Delaunay triangulation, because the triangles are determined by the adjacency of the points, a triangle between two adjacent contour lines will be constructed with the three closest points from the two contour lines, if there is no problem triangle occurring in the triangulation. Since the slopes between each pair of contour lines are represented by the triangles composed of closest points in Delaunay triangulation, the consistency of the slope between two adjacent contour lines is represented properly. In Scarlatos' method, however, the links between contour lines are restricted in the trapezoids. Therefore, when two adjacent contour lines trend mainly in the north-south direction, the triangles in between will be similar to the Delaunay triangulation. However, if the two contour lines trend mainly in the east-west direction, the trapezoids between the two contour lines will be long in the X direction and narrow in the Y direction (figure 3.3). In this case, the slope between the two contour lines may be varied because they are determined by many triangles.

Figure 3.3 Triangles vary with the direction of contour lines

Summarily, Scarlatos' method can solve the problem of triangle crossing contour lines, but with the cost of decreasing the representation quality of the relief. But, the problem of spurious horizontal triangles has not been solved in this method.

3.2.2 A. Christensen's method.

Christensen's method can also be called the "medial axis transformation" method. It generates a medial axis, or midline, between each pair of adjacent contour lines, and then constructs Delaunay triangulation from a point data set composed of the vertices of the contour lines and of the medial axes (for details, please refer to Christensen, 1987). As the author outlines, the "Medial Axis or midline, of a closed shape or polygon, is, roughly, a network of lines whose elements are equidistant from the closest pairs of elements in the shape. The Medial Axis is defined in vector environment. In a raster environment, it corresponds to the skeleton of a shape. In computer operations, the Medial Axis transformation corresponds to the raster 'thinning' or 'skeletonizing' operation" (Christensen, 1987: 61). The author recommends that the medial axes be abstracted in raster format, because "advantages of determining the Medial Axis in raster rather than in vector mode are simplicity in programming, robustness, and perhaps time performance" (Christensen, 1987: 62).

Figure 3.4 "Medial axes" of Christensen's method

Christensen's method avoids the problem of triangle crossing contour lines "by performing Delaunay triangulations in between adjacent contours, which means that the entire map would be covered with many triangulations, each of them executed independently of the others" (Christensen, 1987: 60). In Christensen's method, because the medial axes are abstracted as the "skeletonizing" procedure in raster format, the medial axis between adjacent contour lines must be equidistant to the contour lines. The adjacent contour lines can be two contour lines with the same elevation or different elevations, or two sections of one contour line (figure 3.4). The equidistance of the medial axis to the adjacent contour lines ensures that, in each triangle, there must be at least one vertex from the medial axis. Since the elevations on the medial axis must be different from the adjacent contour lines, the problem of horizontal triangles can be completely avoided.

Figure 3.5 Different precisions between contour lines and the medial axes.

The major disadvantage of this algorithm is its efficiency problem when applied to a large data set, because of the difficulty in generating the medial axes. Although it is relatively simple to obtain the midlines through a thinning (skeletonizing) algorithm in a raster format, to convert contour lines from vector environment (most digitized contour lines are

stored in vector format) into raster, and convert the medial axes back to vector environment will cost large amounts of computing resources. The precision of the medial axes must be restricted by the selected resolution of the raster matrix. In practice, the raster matrix can hardly have the same resolution as the vector based contour lines, so that the vertices on the medial axes, after conversion into vector format, will probably not be exactly in the middle of the two adjacent contour lines. These lower precision points may lead to a distortion on the slopes between adjacent contour lines (figure 3.5), and leave some horizontal triangles unsolved (figure 3.6). On the other hand, although the medial axes can effectively prevent most of the horizontal triangle problems, it is not necessary to generate medial axes everywhere between adjacent contour lines, because the problem occurs only in some specific regions as described previously. To insert medial axes between each pair of contour lines will considerably increase both the storage space required and computing time.

Figure 3.6 Some horizontal triangles cannot be eliminated with lower precision medial axes.

3.2.3 M. Brändli's method.

Brändli's method can also handle the two problems -- "triangles crossing contour lines" and "spurious horizontal triangles". The most significant characteristic of Brändli's method is that, unlike most other approaches, it is not focused on finding out a global

algorithm to prevent the problems occurring in contour based TINs, but employing some special functions to process only the regions where the problems occur. It distinguishes the "problem triangles" and re-constructs that part of the triangulation by relaxing the

Figure 3.7 Problem of triangle crossing contour line is solved by relaxing Delaunay criterion.

Delaunay criteria, and make the triangulation topographically correct. For example, in order to solve the problem of triangle crossing contour lines, the criterion can be determined that the two points can be linked together only if they are derived from the same contour line or the two adjacent contour lines (figure 3.7). For many spurious

Figure 3.8 Examples of horizontal triangles which can also be eliminated by relaxing Delaunay criterion.

horizontal triangles occurring, the criterion has to be changed to: if two vertices of a triangle are derived from the same contour line, the third one must be derived from the

other contour line (figure 3.8). But when a valley is long, with a gentle slope on the bottom, there may be many spurious horizontal triangles distributed along the bottom of the valley. Obviously, if the valley is crooked, it may be impossible to re-construct that

Figure 3.9 Examples of horizontal triangles which cannot be eliminated by relaxing Delaunay criterion.

part of the triangulation no matter what criteria are applied (figure 3.9). One of the most significant advantages in Brändli's method is the ability to handle the problem like this. As shown in figure 3.10, the upper contour line forms a "sack" shape at the bottom of the valley. The triangles inside the sack are sure to be horizontal. On the outlet of the sack,

Figure 3.10 Horizontal triangles in a crooked valley are eliminated by inserting points.

there is normally a contour line with the elevation value one contour interval lower than the upper one. When these spurious horizontal triangles, together with a slope triangle connected to the lower contour line, form a convex polygon with their outlines, the triangles inside this convex polygon can be re-constructed by

connecting all vertices on the upper contour line to the vertex on the lower contour line. If the sack is narrow and crooked, the polygon formed in the same manner may form a concave shape. In this case, since some of the vertices on the upper contour line may not be able to connect to the vertex of the lower contour line without crossing the upper contour line, a number of supplementary points are inserted at the concave part in the sack to make the re-construction possible (figure 3.10).

In comparison with the other two previous approaches, Brändli's method is a "local" approach which re-constructs the triangulation at the part where the problems occur. Since problem triangles are normally much less prevalent than the correct triangles, a local approach should be more efficient than "global" approaches in terms of saving storage space and increasing processing speed.

However, other problem triangles still remain. Although Brändli's method can solve the spurious horizontal triangles along crooked valleys, the problems are not solved when the valley is not as simple as the one represented in a "sack" shape. For example, if the region of interest is a hilly area, the valleys may be broad and intersect each other (figure 3.11). The bottom of the valleys may not be formed by one contour line as a sack, but several contour lines which have the same elevation but are separated from each other. In this case, the triangles which lie between these contour lines are also spurious horizontal triangles, but cannot be eliminated by Brändli's method. Brändli mentioned this problem in his article and concluded that the drainage system data must be used to provide some

supplementary points in the bottom of these valleys (Brändli, 1991). However, since most drainage system data, such as rivers, are normally more general than contour lines, it cannot be guaranteed that all of the valleys will be covered. To digitize break lines along ridges, valleys and saddle parts is also a difficult and labour consuming task, and makes the significance of using contour lines to construct TIN ambiguous.

Figure 3.11 Valleys intersect together in hilly areas.

3.3 Conceptual Design of AICTIN

From the previous analysis, it can be seen that the efforts to improve contour based TIN have made considerable progress but problems still remain. It is significant to start by focusing on and re-constructing the "problem triangles" in the triangulation instead of finding out a global algorithm to construct new triangulations. But, since problem triangles remain (Scarlatos' and Brändli's method), or the method is difficult to apply because of lower efficiency (Christensen's method), further research is still required.

3.3.1 Improvement based on Delaunay Triangulation

The earth surface is such a complex and irregular surface, that a purely geometrical approach, handling the triangulating problems with a unique algorithm regardless of the relationship between the triangles, the contour lines and the earth surface represented by the contour lines, is unlikely to be both effective and practical. A realistic, and efficient, method should be focused only on the problem triangles after the triangulation is completed.

Delaunay triangulation is selected in AICTIN based on the following considerations: 1) TIN represents the earth surface with small triangular planes, with the edges between triangles being the place where the slope varies. Therefore, with the same set of elevation sample points, a triangulation can represent the earth surface with an optimal shape, where the perimeter of each triangle is as short as possible. In Delaunay triangulation, because each triangle is composed of the three closest points, the perimeter of each triangle in the Delaunay triangulation must be the minimum, so that Delaunay triangulation can represent the earth surface better than other triangulations; 2) As a research topic in computational geometry, Delaunay triangulation has been well researched, and many efficient algorithms to construct Delaunay triangulations have been developed; and 3) In a contour based Delaunay triangulation, if there is not the problem of triangle crossing contour lines, the links between the middle points on the non-contour-segment triangle edges is more or less the same as the "medial axis" in Christensen's method, when the medial axis was generated in vector format (figure 3.12). Because the medial axis is effective in preventing spurious horizontal triangles, the middle points on the non-contour-segment edges of such triangles must be able to play an important role in solving the problems, but avoiding the conversion between vector and raster format.

3.3.2 Relationships between Relief, Contour Lines and a Contour based TIN

Although there are complex variations of relief on the earth surface, all types of landforms are composed of the basic elements -- valleys, slopes, peaks, ridges, and saddles. Different shapes and sizes of the elements represent different landforms. But, since the shapes and sizes of the elements are too complex to directly summarize their relations with the triangles, the concepts of the elements must be further abstracted in the sense of geometry, or even topology. For example, if a valley is broad and steep, and there are no horizontal triangles at the bottom of the valley, the valley can be treated not as a valley,

Figure 3.12 Links between non-contour-segment edges are similar to the medial axes in Christensen's method.

but as two slopes. A valley which is meaningful to triangulation is one in which there are horizontal triangles derived from the contour vertices in the valley, regardless of the shape and size of the valley. In this sense, a ridge has the same topological characteristics as a single valley, a saddle is similar to a valley with two outlets, and a pit is the same as a peak. After the topological abstraction, the relations between triangles and these relief elements are clear. In the rest of the thesis, a "valley" will represent a valley, or a ridge, and a "peak" can also mean a pit.

When the vertices of contour lines are used as individual elevation sample points to construct a TIN, the triangles of the triangulation would have some significant properties differentiated from a normal triangulation constructed by the really scattered elevation points, because the elevation values of these points are all the integral multiples of the contour interval. The triangles of the contour based triangulation can be classified into several groups according to the combination of the elevations of triangle vertices and the triangle edges which may be derived from original contour line segments, or a link between two contour vertices which are derived from different contour lines. In the optimal situation, the triangles should be located between two adjacent contour lines, i.e. the two triangle vertices should have the same elevation value and both of them should be the vertices sequentially in an original contour line, and the third point should have the elevation value one contour interval higher, or lower, than the elevation value of the two points. If the property of the triangle is different from the optimal situation, it may be one of the two problems described previously.

According to the elevations of triangle vertices, all triangles in the triangulation can be classified into three categories:

Figure 3.13 Contour lines are interrupted originally on the maps.

1) The elevation difference in one triangle is greater than one contour interval

In this case, there are two possible types of triangles: 1) two triangle vertices have the same elevation value and the third one has an elevation value two or more contour intervals higher, or lower, than the first two have; and 2) the three triangle vertices have the elevation value different from each other, and the difference between the highest and the lowest is greater than one contour interval. Obviously, the edge linking the highest and the lowest vertex crosses at least one contour line. However, a special case must be considered that in some regions where the contour lines are too close together to be represented clearly, according to cartographic principles, it is allowed to interrupt some of the contour lines in this region, in order to represent the contour lines clearly. Now, the problem is that although the triangle must cross some contour lines when the elevation difference in the triangle is greater than one contour interval, it cannot be determined, from this triangle, whether or not the contour line has been originally interrupted on the maps (figure 3.13). Therefore, some other methods must be used to determine the triangle crossing contour lines.

2) The elevation difference in one triangle is equal to one contour interval

Although most triangles which belong to this type are correct, some problem triangles may also have the same property. An example is illustrated in figure 3.14. This is also an example which provides proof that it is not sufficient to solve the problem of triangle crossing contour lines from the analysis on elevation difference of triangle vertices. The detection of the triangles crossing contour lines will be discussed in section 3.3.3.

Figure 3.14 Some triangles crossing contour lines have normal elevations on their vertices.

3) The elevation values of the triangle vertices are equal

Obviously, this type of triangle is a horizontal triangle. Furthermore, according to the edge properties of the horizontal triangles, they can be further classified into four groups. A detailed analysis of these groups of triangles will indicate that each group of triangles represents a certain area on the earth surface and has a specific relationship with the associated contour lines.

Horizontal triangles whose three edges are derived from one contour line

Determined by the nature of contour lines, all contour lines, no matter whether their elevation values are the same or not, cannot intersect each other. Therefore, when the three edges of a triangle are all derived from contour line segments, rather than the links between contour lines, the triangle must represent a self closed contour line with three vertices (This contour line will have four vertices in digital format, in which the initial one and the final one are identical). That self closed contour line can be the peak of a hill, or the bottom of a pit (figure 3.15a).

Horizontal triangles whose two edges are derived from one contour line

When the two edges of a triangle are derived from contour line, they must be derived from the same contour line, because the two edges must be linked together. The three vertices of the triangle must be the three sequential vertices derived from that contour line (figure

3.15b). This type of triangle must be located at the bottom of valleys where the contour lines turn from one side to the other side of the valleys.

Horizontal triangles which have one edge of contour line segment

Most spurious horizontal triangles are this type of triangle. If a contour line lying on the bottom of a valley can be looked upon as a "sack", this type of triangle is normally distributed in the sack between the outlet and the bottom of the sack (figure 3.15c). In this case, the three triangle vertices are derived from the same contour line, but one of them is not sequential from the other two. In addition, from this type of triangle, another type of valley can also be recognized although the valley is represented by two contour lines with the same elevation value (figure 3.15d). This type of triangle can also be distributed in the middle of a long and narrow peak (figure 3.15e), or saddle (figure 3.15f), because a saddle can also be topologically considered as a short valley which has two outlets, or two intersections with other valleys.

Horizontal triangles in which none of the edges is derived from contour line segments

If a triangle is horizontal, but none of the edges is a contour line segment, it can be concluded that the triangle is located at an intersection of three valleys, because the three vertices of the triangle are derived from the three different contour lines, or the three different parts of the same contour line (figure 3.15g).

3.3.3 Detection of Problem Triangles

The detection of spurious horizontal triangles is easy because the edge properties of the horizontal triangle can be directly used as discussed in the last section. However, the triangles crossing contour lines must be detected using another method which will be discussed in this section.

As mentioned previously, when there is a triangle in which the elevation difference is greater than one contour interval, although it is known that the triangle crosses some contour lines, it cannot be determined whether or not the contour line is interrupted originally on the map. Therefore, instead of detecting the problem triangles from the elevation difference in the triangles, another method is employed in the project, which uses the sequential information of the contour vertices to detect whether or not the two sequential contour vertices are crossed by triangles. If yes, the triangles which cross the two sequential contour vertices can be found and processed.

- a) Three-contour-segment triangle
- b) Two-contour-segment triangle
- c-f) One-contour-segment triangle
- g) Non-contour-segment triangle

Figure 3.15 Spurious horizontal triangles

Because Delaunay triangulation is such that it covers the whole study area with triangles, there is no blank space or overlap between the triangles. Therefore, it can be determined that if any two sequential contour vertices are the two vertices of ONE triangle, the link of these two contour vertices must be one edge of the triangle, and cannot be crossed by other triangles. In other words, if the two sequential contour vertices are not located on the same triangle, the segment between the two contour vertices must be crossed by at least two, or maybe more, triangles (figure 2.5). Using the sequential information of contour vertices has another advantage in that it can detect all triangles crossing contour lines even though the elevation difference of the triangle may be equal to one contour interval (figure 3.14).

3.3.4 Splitting Problem Triangles by Inserting Supplementary Points

After all of the problem triangles are detected, there are two ways to solve them. One way is to re-construct the part of triangulation with non-Delaunay criteria. But in many cases it is not possible to do the re-construction without inserting supplementary points (for details, please refer to Brändli's method). Because the insertion of supplementary points is often inevitable, AICTIN splits the problem triangles by inserting points within the triangles or on the non-contour-segment edges of the triangles. For the triangles crossing contour lines, the points can be inserted along the crossed contour line at the location where the non-contour-segment triangle edges and the crossed contour lines intersect together. For the spurious horizontal triangles, the points can be inserted at the middle points of the non-contour-segment edges, because, as mentioned previously, the link of these middle points is theoretically identical to the "medial axis" introduced by Christensen. The difference between the two is that the middle points in AICTIN have

higher precision because they are not converted from raster format, and these points are only applied to the horizontal triangles, rather than everywhere.

3.3.5 Elevation Interpolation for the Inserted Points

Since the elevation values of the inserted points are unknown during the inserting procedure, it is necessary to interpolate their elevation values afterwards according to their spatial relationships with the known elevation points, i.e. the contour vertices and some scattered elevation points. Because the links between inserted points represent the discontinuities, i.e. break lines, of the surface, this is an important advantage which is helpful in the elevation interpolation for the inserted points.

Before selecting interpolation method for the inserted points, some special characteristics of these points should be considered. First, these points have special topographical meanings and are located at specific regions, i.e. they are located at the discontinuities on the surface represented by the TIN. Second, they are not independent from each other but constructed in a triangulation, so that the spatial relationship between these points and the known elevation points can easily be obtained. Because of these characteristics, the elevations of these points can be interpolated by linking them together with the known elevation points. As described previously, these points are inserted roughly along break lines, so that all of these points can be linked together as a break line network. Furthermore, the break line network can also be separated into groups at the intersections with contour lines. Because the end points in the break line groups are known elevation points for intersecting the contour lines, the elevations of the points in each break line group can be interpolated individually along the break lines (figure 3.16). To interpolate elevations along break lines also has the advantage that it can guarantee the elevations

along the break line are decreased successively from the upper contour line to the lower one.

Figure 3.16 Elevation interpolation along break lines.

3.4 Summary

This chapter has analyzed the current development on the improvement of contour based TIN, and presented the conceptual design of AICTIN, which includes: the feasibility analyses on the improvement of a contour based Delaunay triangulation, the relationship analyses between relief, contour lines and the triangles in the triangulation, the discussions about the detection of the problem triangles, the method of solving the problem triangles by inserting supplementary points, and the method of interpolating elevations for the inserted points.

4 ALGORITHM DESIGN FOR AICTIN

4.1 Introduction

Algorithm design is a key step from the conceptual design to the final implementation. This chapter concentrates on the algorithm discussions for all cases that occur in the splitting of problem triangles and the elevation interpolation for the inserted points in different regions. The whole procedure is decomposed into small modules, and the logical relationships between modules are emphasized.

Figure 4.1 The triangles crossing the contour line are detected sequentially.

4.2 Splitting Triangles Crossing Contour Lines

When a contour segment composed of vertex A and vertex B is crossed by some triangles, the triangles crossing the contour segment can be detected in the following ways: 1) from vertex A, check each of the triangles which contains A as a vertex of the triangle. If its two edges linking to vertex A extend in the same direction as the contour segment, but are distributed on different sides of the contour segment, this triangle must be the first triangle which crosses the contour segment, and its third edge must be the edge crossing the contour segment; 2) another triangle which shares the same "crossing edge" with the last "crossing triangle" must be another "crossing triangle"; and 3) if the vertex opposite the "crossing edge" in the last "crossing triangle" is not vertex B, there must be another "crossing edge" in the triangle, which can be determined by checking the position of that

opposite vertex. If that vertex is on the left side of the contour segment, the right edge is "crossing edge" in the triangle, which can be determined by checking the position of that opposite vertex. If that vertex is on the left side of the contour segment, the right edge is the "crossing edge". If it is on the right side, the left one is the edge. If it is on the segment, it must be vertex B. Steps 2 and 3 are repeated until the triangle which contains vertex B is found (figure 4.1).

The crossed contour segment can be connected by inserting one point on each "crossing edge" at the location where the edge crosses the contour segment, then the two triangles sharing the edge, as well as the edge itself, can be split by linking the inserted points to the vertices on both triangles opposite to the edge. After all "crossing edges", and the associated triangles, are split sequentially, the problem of triangles crossing contour lines has been solved (figure 4.2).

Figure 4.2 The edges and the associated triangles are split sequentially.

Although the split triangles may no longer be Delaunay triangles, there are many advantages in this method of splitting triangles. It should be noted that because the

splitting operation is restricted to a limited number of triangles, it is easy to handle, and it is not necessary to reconstruct the surrounding triangles. Since the number of triangles to be split is generally less than the number of normal triangles, these "non-Delaunay triangles" will not significantly influence the quality of the whole triangulation.

4.3 Splitting Spurious Horizontal Triangles

The spurious horizontal triangles should be processed after all problems of triangle crossing contour lines are solved, because some new horizontal triangles may be created during the solution (figure 4.3). The method used in splitting the spurious horizontal triangles is similar to the method of solving the triangles crossing contour lines. The difference is that instead of inserting points along the crossed contour lines, the points are inserted at the middle of the non-contour-segment triangle edges. As discussed in chapter 3, the links between these inserted points form break lines of valleys, ridges, and saddles.

Figure 4.3 Some horizontal triangles are created after splitting triangles crossing contour lines.

Since the different types of horizontal triangles represent different parts of the relief and also have different relationships with the break lines, the splitting methods for these types of triangles must be different as well.

4.3.1 Non-Contour-Segment Triangles

As discussed in chapter 3, a horizontal triangle in which none of the edges is derived from contour lines represents an intersection of three valleys. Therefore, there must be a point

around here at which the three break lines intersect together. Because the break lines are assumed to be in the middle of the valley, the three break lines in the triangle should be coincident with the three perpendicular bisectors of the triangle edges, and the intersection point of the three break lines should be the circumcenter of the triangle as well. Therefore, the triangle should be split into six smaller triangles from the circumcenter to the three triangle vertices and the middle points of the three edges, where the splitting lines which connect the three middle points of the edges will be the break lines (figure 4.4 a). If the circumcenter is outside the triangle, or on one edge of the triangle, the middle point on the edge which is closest to the circumcenter will be taken as the intersection point of the break lines. In this case the triangle will be split into four triangles instead (figure 4.4 b).

Figure 4.4 Splitting non-contour-segment triangles

4.3.2 Two-Contour-Segment Triangles

This type of triangle represents the turning point of the contour line at the bottom of a valley. It should be split into two triangles from the middle point of the non-contour-segment edge to the opposite vertex of that edge. The splitting line will be part of the break line of the valley (figure 4.5).

Figure 4.5 Splitting a two-contour-segment triangle

4.3.3 One-Contour-Segment Triangles

Since this type of triangle is located at the middle part between two contour lines in a valley, long and narrow peak, pit, or saddle, the break line should pass through the middle points of the two non-contour-segment edges of each triangle. But, in practice, when the triangle is split by the break line, the triangle will be decomposed into one triangle and one quadrilateral, so a further splitting should be applied to the quadrilateral to make the triangulation correct (figure 4.6).

Figure 4.6 Splitting an one-contour-segment triangle

Figure 4.7 Splitting a full-contour-segment triangle

4.3.4 Full-Contour-Segment Triangles

This type of triangle represents a self closed contour line on the top of a hill or bottom of a pit. It is necessary to determine a point inside the triangle with an elevation value higher than the closed contour line if it represents a hill, or lower if it represents a pit. However, the triangle should not be split from the circumcenter, because the circumcenter can be outside the triangle. The centroid of the triangle is used in the project to split this type of triangle. The centroid of a triangle can be determined by the intersection point of the three central lines of the triangle (figure 4.7).

Figure 4.8 Triangle A has four edges after the neighboring triangle is split.

4.3.5 Processing Sequence for Splitting Spurious Horizontal Triangles

The processing sequence of each type of horizontal triangle is important, because an appropriate sequence is helpful in making the whole procedure logically clear and easy to

implement. For example, when a two-contour-segment triangle is split into two small triangles, the adjacent horizontal triangle should be split correspondingly, because this triangle is no longer a triangle after its neighboring triangle is split (figure 4.8). If the

Figure 4.9 Variation of the number of the triangle vertices.

processing sequence was not considered, the vertex number of the horizontal triangles to be split would vary from 3 to 6 (figure 4.9). With varying vertex numbers, it will be difficult to detect the triangle properties and split the horizontal triangles. For a single valley (there is no branch valley within one contour interval), processing the horizontal triangles sequentially along the valley can avoid the problem of varying vertex numbers, because the types of triangles in a single valley are simple: The process can start from a "two-contour-segment triangle", pass by several "one-contour-segment triangle" and end at a slope triangle, or vice versa. Since the triangles are split sequentially along the valley, any triangle whose vertex number is changed by the splitting of it's neighboring triangle, will be guaranteed to be the next triangle to be split. But in a hilly area, valleys often intersect together within one contour interval, and the break lines along the valleys may form a network. To process the horizontal triangles in this area requires that all of the triangles passed by the break line network are gone over. Because the "non-contour-segment triangle" is a connection of three valley branches, and must be passed through

twice, the implementation will be difficult and complicated. In consideration of the special characteristic of the "non-contour-segment triangles", these triangles are split first. Furthermore, in order to avoid influencing the neighboring triangles, these triangles are split by linking the circumcenters only to the three vertices (figure 4.10). If the

Figure 4.10 Splitting the non-contour-segment triangle into three triangles, if the circumcenter is inside the triangle.

circumcenter is outside the triangle, the triangle will be split into two by using a substitute of the circumcenter. However, for the triangle whose circumcenter is outside the triangle, the neighboring triangle adjacent to the splitting edge must also be correspondingly split from the circumcenter substitute to the opposite vertex of the neighboring triangle to keep the triangulation correct (figure 4.11). After the non-contour-segment triangle is split, the

Figure 4.11 Splitting the non-contour segment triangle into two triangles as well as the neighboring triangle, if the circumcenter is outside the triangle.

circumcenter, or the substitute of the circumcenter, can be taken as the intersection of the three break lines because this point must have an elevation value different from that of the associated contour lines, although the exact elevation value is unknown yet. Correspondingly, the three, or four, newly formed triangles can now be considered as slope triangles rather than horizontal triangles. After all the "non-contour-segment triangles" are split, the complex horizontal valleys will no longer exist, and all horizontal triangles are restricted to single valleys and are easily split.

4.4 Elevation Interpolation for Inserted Points

As discussed in chapter 3, a group of break lines which are separated from other groups by contour lines can be considered as an individual unit in which the elevations of each point can be interpolated by using the known elevation points in the unit. If the known elevation points have different elevations (they are normally equal to one contour interval, or less than that if there are other known elevation points), it will be possible determine whether this unit should be located in valleys or ridges, or whether, the unit should be located at peaks, pits, or saddles. Units in different locations require different interpolations which will be discussed respectively.

4.4.1 Elevation Interpolation for Valleys and Ridges

Based on the assumption that the slopes between two adjacent contour lines are consistent, the slope along the bottom of a valley between two contour lines is also assumed to be consistent, so that a linear interpolation can be used for the break line units in valleys and ridges. The elevation for each point in the unit is calculated with the expression shown below:

$$E_p = (E_h - E_l) * (D_{pl} / D_{hl}) + E_l$$

where

Ep: the elevation to be interpolated at the current point,

Eh: the elevation on the higher known elevation point,

El: the elevation on the lower known elevation point,

Dpl: distance from the current point to the lower known elevation point along the break line,

Dhl: total break line length from higher to lower known elevation points.

When the interpolating unit represents a single valley, or ridge, it is easy to calculate the elevation for each point along a break line. However, when the unit represents a complex valley, there may be more than two valleys intersecting each other within the unit, especially in hilly areas (figure 4.12). The break line unit here is actually a network composed of several valley branches. In this type of unit, since there may be more than two known elevation points with higher and lower contour values, the different

Figure 4.12 Break lines intersect together in one unit.

combination of the pair of higher and lower known elevation points will lead to a different path through the network. Even with the same pair of known elevation points, there may also be more than one possible path (figure 4.13a). On the other hand, each point in the unit may be passed by several paths composed of different known elevation points (figure 4.13b). Therefore, before using the previous expression to calculate the elevation for each point in the unit, it is necessary to determine a path for each point, in order to obtain the parameters required by the expression. The question is how to determine the path for

Figure 4.13 Example of
a) There are two paths from A to D;
b) Many paths pass by point C.

each point. Theoretically, when a point is located in a main valley, the path used to calculate the elevation for that point should be identical to the main valley. But since the real topographical break line information is normally not available together with digital contour lines, it is necessary to determine every path in a network based on the break line network itself and the known elevation points. Although the paths calculated from this information may not be exactly equal to the real break lines of valleys, for each point the interpolated elevation based on these paths is not much different from that based on the

real break lines, because all of the points in the unit are restricted between the upper and the lower contour lines, i.e. within one contour interval.

4.4.1.1 Elevation Interpolation for Valleys

Since there may be more than one possible path from a higher known elevation point to a lower one in an interpolating unit, it is important to define the criteria to match the interpolated valley paths as close as possible to their real valley paths. According to the information available in the unit, the criteria of valley paths can be defined as: the geometrically shortest path in the unit from a specific higher known elevation point to a lower one. This criterion also accords with the principle of drainage, because from a certain higher altitude to a certain lower altitude, the water should flow along the shortest and steepest slope.

With the criterion defined previously, network searching, which is similar to the state space searching in AI (Artificial Intelligence), can be applied here to find out all the valley paths. Network searching starts from a given start point, ends with a destination point, and records all of the intermediate points passed through. If there is more than one path from the start point to the destination point, the network searching must search all possible paths until it reaches the one which accords with the given criteria. In this project, the network searching will search each possible path and record the path length. By comparing the path lengths of the current path and the previous one, and taking the shorter one for comparison with the next path, the shortest one will be eventually found, and taken as the interpolated valley path from the higher to the lower known elevation point.

Since one interpolation unit in a hilly area may be very complex and contain many known elevation points, it is necessary to ensure that each known elevation point must be linked

with at least one valley path to another known elevation point with a different elevation. However, a problem may occur in that some valley paths may share a common part. For example, they start from different higher known elevation points, but end up with the same lower known elevation point, and join together somewhere before reaching the lower known elevation point (figure 4.13b). Because their path lengths are normally different from each other, the points in the common part may be assigned different interpolated elevation values from different valley paths. As shown in figure 4.13b, the points in the common part will get a higher elevation value from a shorter path than from a longer one. If the average value is taken as the elevation of each point in the common path, a slope error may occur in the longer valley path i.e. the elevation is not decreased successively from the higher to the lower known elevation point in the longer valley path (figure 4.14).

Figure 4.14 A slope error occurs with the elevation averaged by different paths.

The larger the length difference between the valley paths is, the larger the difference of interpolated elevations will be in the points in the common path. Therefore, it is more likely to lead to a slope mistake. In addition, because the longer valley path probably represents the main valley in the network of valleys, it is more important to correctly interpolate the elevation values in the main valley than those in branch valleys. It would be better if the main valley path could be distinguished from all other valley paths, and that the elevations along the main valley path, as well as the elevations in the common part

with other valley paths, are interpolated along the main valley path. In this project, the main valley path is defined as the longest valley path in all of the interpolated valley paths in the network. Although the longest valley path may not be the main valley in a topographical sense, it is effective to take the elevation value interpolated from the longest valley path as the final elevation value in the common part of several valley paths in order to ensure the elevations in all valley paths are decreased successively from the higher to the lower known elevation point, and to avoid the slope error along the main valley.

After the elevation values in the longest valley path are interpolated, the other paths which share common parts with the longest valley can be processed to interpolate the elevation values on these paths. For better accuracy, the interpolation should be started from the higher known elevation point to the point whose elevation has been assigned during the interpolation of the main valley path, rather than the original lower known elevation point of the path, so that different interpolated elevation values for the same point can be avoided. Because the longest valley path may be the most important valley in the network, the interpolating sequence of all valley paths should be done from the longest to the shortest in one unit.

Since it is not guaranteed that all interpolated valley paths can cover all points in the interpolation unit, the elevations of the rest of the unknown elevation points must be interpolated afterwards. Since the interpolated valley paths in a network are defined as the shortest paths from specific higher known elevation points to lower known elevation points, the remaining break lines between interpolated valley paths should no longer be valleys, but saddles. Therefore, all the remaining unknown elevation points should be treated as points on a saddle, which will be discussed in section 4.4.2.

4.4.1.2 Elevation Interpolation for Ridges

The elevation interpolation for ridges is almost the same as that for valleys. The only difference is that the common parts of ridge paths are close to the higher known elevation points. Because this difference does not influence the interpolation, the same interpolation procedure as that for valleys can be directly applied for ridges. Therefore, it is not necessary in practice to differentiate ridge units and valley units.

Figure 4.15 Interpolation unit of a peak and a saddle.

4.4.2 Elevation Interpolation for Peaks, Pits and Saddles

The interpolation unit of peaks or saddles also have known elevation points. But, unlike the interpolation unit of valleys or ridges, the elevation of these points are all the same (figure 4.15). The difference between a saddle unit and a peak unit can be recognized in this way: All unknown elevation points in a saddle unit must be linked to some known elevation points which are not within the break line network and have elevation values different from the known elevation points in the unit. The points in a peak unit, on the other hand, must be linked to some known elevation points which have the same elevation value as the known elevation points in the unit.

Figure 4.16 Extreme elevation point in the interpolation unit of a peak.

An important stage of elevation interpolation for both peak and saddle units is to determine which point in the unit has the elevation most different from the known elevation points in the unit, i.e. the extreme elevation point in the network, and its elevation as well. Based on the assumption that there are no scattered elevation points at peaks or saddles on the contour maps, the location of the extreme point is defined in the project as follows: In a peak unit, it should be the point which is the farthest away from the surrounding contour line (figure 4.16). In a saddle unit, the location should be the

Figure 4.17 Extreme elevation point in the interpolation unit of a saddle.

point which has the shortest distance to an known elevation point out of the network (figure 4.17). The elevation for the extreme point in a saddle unit can be interpolated by two known elevation points weighted with their distances to the extreme point. Those two known elevation points should be the closest to the extreme point, but have different

elevation values. One is an known elevation point in the network, and the other one is out of the network.

The elevation for the extreme point in peak units cannot be interpolated with the linear interpolation method used in the project, because all the known elevation points in the network or directly linked to the extreme point have the same elevation value. Therefore, it is necessary to employ a non-linear interpolation method to interpolate the elevation of the extreme point in the peak unit. Because pit units have the same topological characteristic as peak units, the extreme point in pit units can be processed in the same manner. After the elevation interpolation of the extreme point, the remaining points in the unit can be handled similarly to the elevation interpolation for valleys and ridges.

Figure 4.18 Non-linear elevation interpolation for the points on the outline of the triangulation.

The non-linear interpolation for extreme points can also be applied to the interpolation units which reach the outline of the triangulation. In this type of unit, the points which are on the outline of the triangulation must play the same role as the other known elevation

points, in order to interpolate the elevations for other points. Therefore, the elevation of these points must be interpolated before other points, and, must be interpolated non-linearly (figure 4.18).

The interpolation sequence is important. The elevations in peak units, pit units and the units reaching the outline of the triangulation must be interpolated after the elevations in all other units are interpolated, because some neighboring points out of the self closed contour line must be used to calculate the coefficients required by the non-linear interpolation. If the triangles outside the self closed contour line happen to be horizontal triangles in a valley unit, these points may have the same elevation values as the self closed contour line, or an elevation yet unknown (figure 4.19). With such points, the elevation of the extreme point cannot be correctly interpolated. However, after all valley, ridge, and saddle units are processed, the neighboring points out of the self closed contour line must have elevations different from the elevation of the contour line, so that the elevation of the extreme point can be interpolated with better coefficients.

figure 4.19 The elevation at point A is difficult to non-linearly interpolate before the surrounding valley unit is interpolated.

For a complex network of peaks, pits, or saddles, it is designed in AICTIN that once one extreme point is determined and its elevation is interpolated, the rest of the points in the

unit will be treated as ridges or valleys. Therefore, the valley paths in the network will be searched again, by taking the extreme point as the known elevation point in the unit which is different from the other known elevation points on contour lines. The extreme point can be a higher elevation point for peak units, a lower elevation point for pit units, or both for saddle units (figure 4.20).

4.5 The Relationship with Scattered Elevation Points

On topographic maps, the contour lines are often used together with scattered elevation points to represent landforms. These scattered elevation points are normally distributed in the area of peaks, pits, and saddles, to indicate the elevations there, because they cannot be represented with contour lines. In fact, these points can also be considered as contour lines with different contour intervals (those "contour lines" are so small that they have to be represented as points), so all of the methods for contour lines discussed previously can be directly applied here without any change.

Figure 4.20 After the elevation on point C is non-linearly interpolated, the break line AB has been separated into AC and BC..

4.6 Summary

This chapter has discussed the algorithms for splitting the triangles crossing contour lines and the spurious horizontal triangles, as well as the algorithm of interpolating elevations for the inserted points. For each type of spurious horizontal triangles, the specific splitting algorithm has been presented. The elevation interpolations for inserted points in different

regions, such as valleys, ridges, peaks, pits, and saddles, have been discussed respectively. The processing sequence for splitting spurious horizontal triangles and interpolating elevations for inserted points has been emphasized.

5 IMPLEMENTATION AND DATA TESTING

5.1 Introduction

AICTIN is an approach designed to solve the problems occurring in contour based TIN. It includes many algorithms for different cases. To prove these algorithms feasible, implementation is a good method. In addition, implementation and testing can also provide feed back on the disadvantages of the algorithms for further improvement. Implementation and testing with real data provide a comprehensive examination of the algorithms in respect to computing speed, storage space, and reliability. During and after the implementation, more than 10 data sets of digital contour lines were used to test the programs. This chapter will introduce some important points in the process of implementation and data testing.

5.2 Implementation

The implementation was carried out on SPANS, a PC based GIS software product developed by TYDAC. All programs related to the project were developed with Microsoft C/C++ 6.0 for OS/2 operating systems. The programs consist of mainly four parts: 1) abstracting elevation sample points from contour lines; 2) generating Delaunay triangulation; 3) solving the problem of triangle crossing contour lines and the problem of spurious horizontal triangles by inserting supplementary points; and 4) elevation interpolation for the supplementary points. The detailed discussions are given as follows:

5.2.1 Abstracting Elevation Points from Contour Lines

The points used for generating triangulation can be abstracted from contour lines in different ways. One is to abstract the points with a certain interval along the contour lines

in order to prevent the problem of triangles crossing contour lines. However, as discussed in chapter 3, whether a contour segment is crossed by triangles depends not only on the intervals of the points on the contour line, but also the distances between the adjacent contour lines. Therefore, an effective interval of points must be less than the shortest distance between contour lines in the whole area. But, to measure the shortest distance between contour lines requires much computing time, and the intervals of the abstracted points may be too small to be necessary in many other places. Since the implementation of the project has a specific process to solve the problem of triangles crossing contour lines, the intervals of the abstracted points are no longer problems which must be worried about. Thus, only the vertices of the contour lines which are significant to represent the shape of contour lines are abstracted from the contour lines taken as elevation points for generating Delaunay triangulation. Special attention should be paid to the self enclosed contour lines, because there must be two identical end points of the contour line represented in digital format. In order to avoid confusion, only one of them can be used as a sample point.

5.2.2 Generating Delaunay Triangulation

Delaunay triangulation, as a type of triangulation with specific properties, has been well researched and widely used in many computer related applications. Since the point set to be triangulated is often a large amount of data, the efficiency of an algorithm for generating Delaunay triangulation is important due to its significant influence on computing speed. Therefore, it is necessary to briefly review the algorithms for generating Delaunay triangulation, before choosing one of them as the algorithm used in the project.

Figure 5.1 Swap of triangle edge

5.2.2.1 A Brief Overview of Delaunay Triangulation Algorithms

In practice, not only the computing time of an algorithm is important, but also the simplicity and ease of implementation. The algorithms concerned will be analyzed mainly from the aspects of computing time and simplicity of implementation.

In the process of generating Delaunay triangulation, an unavoidable operation is to swap a common edge of two adjacent triangles to the other two opposite points of the common edge (figure 5.1), when it is necessary according to the criteria of Delaunay triangulation.

Figure 5.2 The circumcircles of the two triangles before and after the swap.

The definition of Delaunay triangulation can be directly used here to make the decision if a swap is necessary, i.e. if one triangle vertex opposite to the common edge is within the circumcircle of the other triangle, the common edge of the two triangles should be swapped (figure 5.2). Obviously, to judge the necessity of and to do the swapping should take more or less the same time in all Delaunay triangulating algorithms. The process which makes the algorithms different from each other in respect to computing time is finding the closest three points for each triangle.

The Delaunay triangulating algorithms can be mainly summarized as two typical types: $O(N^2)$ and $O(N\log N)$ algorithms. N refers to the number of points to be triangulated. $O(N^2)$ and $O(N\log N)$ represents the computing time taking the number of points as the counting unit. A typical $O(N^2)$ Delaunay triangulating algorithm is to take the first three points to construct a basic unit of the triangulation, then insert the remaining points into the triangulation one by one and re-construct the triangles associated to the newly inserted point. Because it is necessary to check all existing triangles in order to locate the point to be inserted, the total checking time will be $O(N^2)$. The disadvantage of $O(N^2)$ algorithms is that the checking will increase by N^2 times when N increases. However, the advantage of them is that they are simple and easily implemented. On the other hand, the $O(N\log N)$ algorithms are optimal in terms of time consumption. A typical algorithm for triangulating scattered points in $O(N\log N)$ time is the so called "divide and conquer" algorithm. The principle of "divide and conquer" used in generating Delaunay triangulation is that it sorts the points with the X coordinates at first, then bisects the point set recursively, i.e. divides the whole point set into two equal quantitative subgroups, and each subgroup will also be divided further into two equal quantitative groups. This procedure is repeated until the number of points in one group is less than four and can simply be constructed into a

Figure 5.3 A "divide and conquer" algorithm of triangulation.

triangle or a single edge, which are the basic elements of the triangulation. Then, the following step is the conquer procedure which combines each pair of triangulation elements into one larger triangulation. This procedure is also repeated until all small triangulations are combined together (Preparata and Shamos, 1988). Figure 5.3 shows an example of constructing a simple triangulation with the "divide and conquer" algorithm. From the description above, it can be seen that the "conquer" is actually a converse procedure of the "divide". In a data set with N points, because only proximate $O(\log N)$ times are needed to divide all of the points into the smallest group, and for each division, there are always N points involved. Therefore, the total computing time is $O(N \log N)$. Figure 5.4 illustrates a comparison between $O(N^2)$ and $O(N \log N)$ algorithms in time consumption. From figure 5.4, the advantage of $O(N \log N)$ algorithms in processing of large amounts of data is significant.

Figure 5.4 Time consuming variation of N^2 and $N \log N$ algorithm with increasing of N .

Figure 5.5 Operation flow of the "divide and conquer" triangulation.
D=divide T=triangulate C=conquer

Although divide and conquer algorithms have the advantages in computing speed, they are usually difficult to implement because of the recursive operation. Figure 5.5 illustrates the recursive operation flow for generating the Delaunay triangulation shown in figure 5.3.

Figure 5.6 The points to be linked to the subsequent point can be determined by the outline of the triangulation from the previous point.

For a recursive operation, since a group of data is divided into two subgroups, only one of them can be divided further, the other one must be left "hanging" there. If the data set is large, there will be many subgroups left hung during the procedure. In practice, the C programming language provides the ability of recursive operation which can "hang" subgroups of data by using stacks. But since the data storage and stacks share the same physical memory, it is hardly feasible to use large amount of stack space to record the data processing status, especially on PC's. If the built in recursive operation of C is not used in order to avoid occupying a large amount of memory, it will be difficult to realize the procedure of divide and conquer with a non-recursive operation.

5.2.2.2 The Triangulating Algorithm Used in The Project

The triangulating algorithm used in the project is neither $O(N^2)$, nor $O(N \log N)$, but very close to an $O(N \log N)$ algorithm. It performs like an $O(N \log N)$ algorithm, but is easy to

implement like an $O(N^2)$ algorithm. The algorithm uses a QUICKSORT function built into the C compiler to sort the point set by the X coordinate values, and also the Y coordinate values if the points have the same X coordinate. With a sorted point data set, after the first triangle is constructed, all subsequent points must be outside the existing triangulation, so that it is no longer necessary to check what triangle the next point should be located in. In addition, the point must be able to link to the last point inserted in the triangulation. From the previous point, all other points which should be linked to the next point can be easily determined, because all these points must be on the outline of the triangulation (figure 5.6). Then some swaps will be done, if necessary. Once the next point can, without any over all searching, easily find the points it should be linked to, inserting all subsequent points can be considered basically a linear procedure, because each point would take more or less the same time to be inserted into the triangulation. Although the QUICKSORT takes $O(N\log N)$ computing time, it is a built in function in Microsoft C compiler and runs very fast. Therefore, the algorithm used in the project not only has the advantage of an $O(N\log N)$ algorithm, but is also easy to implement like an $O(N^2)$ algorithm. Figure 5.7 shows the scheme of the triangulating algorithm used in the project.

Another aspect is that the triangulating algorithm uses a linked list structure, rather than a normal array, to record the adjacency of the points for increased computing speed. In the linked list structure, the adjacency of the points is recorded by pointers, rather than their physical relative positions in the memory as the normal array does. Therefore, the adjustment of the adjacencies of points, due to the edge swapping by inserting new points, can be completed quickly, because the adjustment of point adjacencies does not require the adjustment of the position of points in the physical memory, but only the pointers. The

Figure 5.7 Triangulation algorithm used in the project.

advantage of linked list in recording the point adjacencies is that the relationship between points are linked by pointers which record the address of the other related points, regardless where those points are physically located. When a point is removed from the

adjacent point list of another point, only the related pointers are changed, and the memory for that point can be released. If a normal array was used, when a point was removed, all the following points in the memory would have to be moved one position forward. In the same way, when a point was inserted at a certain position, all the subsequent points would have to be moved backward in order to make room for the inserted point. Figure 5.8 shows the procedure of inserting and removing points from a normal array and a linked list. During the implementation, as an experiment, two triangulating programs were tested with the same data set. One uses the $O(N^2)$ algorithm and a normal array, the other uses the algorithm designed in the project and the linked list structure. With a 40,000 points data set, the $O(N^2)$ program took more than 6 hours to generate the triangulation, but the one used in the project took only less than 10 minutes.

5.2.3 Solving the Two Problems in Contour based TIN

Since the concept and algorithm design for solving the two problems in contour based TIN has been discussed in chapter 3 and 4, this section will concentrate on practical issues encountered in the implementation.

5.2.3.1 Splitting of The Non-Contour-Edge Horizontal Triangles

In chapter 4, how to split the horizontal triangles in which none of the edges is derived from contour segments, has been discussed. In order to decompose a complex valley into several single valleys, the "non contour edge triangles" are selected to be split first in the process. When the circumcenter of the triangle is inside the triangle, it is simple to split the triangle into three by linking the circumcenter to the three vertices, because the splitting of the triangle will not influence any other neighboring triangles and will keep the triangulation topologically correct. But if the circumcenter is outside the triangle, the

Figure 5.8 Comparison of insertion and removal operation between two data structures: array and linked list.

middle point on the edge which is closest to the circumcenter will replace the role of the circumcenter to split the triangle, and the triangle will be split into two triangles from this

point to the opposite triangle vertex. Because this split makes the neighboring triangle become a "four-edge-triangle" and destroys the topological correctness of the triangulation, that "four-edge-triangle" should also be split correspondingly. For most of the triangles, there will be no problem splitting them when they become four-edge-triangles, except for the non-contour-edge triangles themselves, because this type of triangles should be split independently according to its own properties, before being split further correspondingly to the neighborhood. The only exception is that the corresponding triangle outside the splitting edge is the same type of the triangle as the current one, and shares the same splitting edge (figure 5.9). Otherwise, the current triangle must be split after the corresponding triangle is split. Since there is a possibility that the corresponding triangle has also the same problem as the current one has, it is necessary to use a stack to solve this problem, i.e. when the corresponding triangle

Figure 5.9 Special case for two non-contour-segment triangles which share the same substitute of the circumcenters.

outside the edge to be split has the same property as the current one, process the corresponding triangle first. If the corresponding triangle has the same situation as the current one, take that triangle as the current triangle and repeat the same procedure until the corresponding triangle can be split passively. Then, split all "hanging" triangles from

the last one back to the first one. Figure 5.10 shows this special case and the splitting procedure.

Figure 5.10 Processing sequence of non-contour-segment triangles whose circumcenter are outside.

5.2.3.2 Splitting Other Spurious Horizontal Triangles

Although it is easy to split the horizontal triangles in a single valley after the non-contour-edge triangles are split, there is another method which is efficient to eliminate horizontal triangles. Instead of splitting "triangle by triangle", splitting "edge by edge" is used in the project. The so called "edge by edge" splitting is used to find horizontal, but non-contour-

Figure 5.11 Eliminating horizontal triangles "edge by edge".

segment, triangle edges, split them, and the triangles on both sides of the edge, from the middle point on an edge to the opposite triangle vertices (figure 5.11). The advantage of using "edge by edge splitting" rather than "triangle by triangle splitting" is that, because all of the two associated triangles are split simultaneously when a point is inserted, the triangulation is guaranteed topologically correct. In addition, it also has the advantage of improving the representation of relief on small saddles. As shown in figure 5.12, the saddle is so small that there is no horizontal triangle to be split. But, the link between two equi-altitude, but separated contour lines will form a "dam", rather than a saddle, between the two tops of hills. Because the triangles here are not horizontal, they cannot be detected and split to represent the saddle. Splitting triangles by searching horizontal, non-contour-segment triangle edge can eliminate all horizontal, non-contour-segment triangle edges, so that all non-contour-segment edges in the triangulation are guaranteed to represent the slope. This characteristic of the triangulation is important for making a better conversion from TIN to contour lines with a new contour interval different from the original one which was used in the construction of the TIN.

Figure 5.12 A small saddle without horizontal triangle

5.2.3.3 Abstracting A Break Line Network from The Triangulation

After splitting spurious horizontal triangles, many supplementary points have been inserted into the triangulation, but their elevations are unknown yet. In order to interpolate the

elevations for these points, it would be better if their spatial relationship could be used. As discussed in chapter 3 and 4, these points can be abstracted into a network structure as an interpolation unit, in which the points will be linked together as the break lines of valleys, ridges, and saddles. The abstraction of all these points can start from one contour vertex linked to a break line, and follow the break line to pick up the other points, until all of the points linked by break lines within one contour interval are abstracted. However, when the unit is a complex network, i.e. many valleys intersect each other in the unit, to trace the valleys one after another is actually a recursive operation, and therefore requires stacks to record the tracing status of each intersection point of break lines. Since there may be many valleys intersected together within one contour interval, especially in hilly areas, the size of the stacks required may be too large to be organized on PCs. In order to avoid the stack problem, the abstraction of all the inserted points is completed not by tracing the break lines one by one, but by collecting all the inserted points, in the neighborhood from each current point, if the points have not been abstracted yet. In comparison with the state space searching technique, based on the theory of graph and applied in many computer related applications, especially in artificial intelligence, the points to be abstracted are similar to the nodes in a graph, and the links between these points (break lines) are the arcs between the nodes. Since to abstract the points from the triangulation can be considered as examining the nodes in the graph one by one, the two previously discussed abstracting methods, are similar to the two commonly used searching strategies, "Depth First" and "Breadth First". Because the abstracting of all break line linked points is similar to the procedure of going over all of the nodes in the graph without any specific criterion, such as finding out a specific node or a path, the "Breadth First" search is simple and easy to implement.

Figure 5.13 An interpolation unit and its representation in a two dimensional array.

5.2.3.4 Determination of The Valley Path Interpolation Unit

Unlike the abstraction of the break line network, determination of the valley paths in the unit is finding a path with a certain criteria. Therefore, a "Depth First" search would be better used here. However, as discussed in last section, a "Depth First" search is often realized by a recursive operation which requires large stack sizes. Since the unit network may be very large in hilly areas, the size of the stack required is probably too large to be dealt with on PCs. In order to make AICTIN work on PCs and handle a large data set, use of a large stack size is avoided. For organizing the network, a two dimensional array with some index numbers was used. As shown in figure 5.13, the points in the unit network and the relationship among them can be stored in a two dimensional array. In the array, each row represents one point in the unit. The first column represents the index

number of the point; the following columns indicate the index numbers of other points which are linked to the point represented in the first column. As determined by the algorithms of splitting triangles, for each inserted point, the number of the linked break lines cannot exceed 4. This is an important advantage for determining the size of the array, e.g. if there is a network containing N points, a $5*N$ array is sufficient to record the information of all the points in the network and the linking relationships among the points. Otherwise, if the number of the maximum links from each point could not be restricted to a certain range, the array would have to be allocated in the size of $M*N$, where M is a number which is guaranteed greater than the maximum number of the links from all of the points in the network, in order to avoid a problem of insufficient memory.

After the break line network is abstracted and organized in the array, the next crucial thing is to search the valley paths (for the detailed discussion about valley paths, please refer to chapter 3 and 4) with a "Depth First" searching method. Although the C language provides the ability to realize the "Depth First" search by a function which can invoke itself recursively, it is not used in the project avoid the problem of stack size. The "Depth First" search is realized by a non-recursive operation which records the points of the possible path in a temporary list. Figure 5.14 represents the flow charts of a recursive search and non-recursive search. In comparison with the recursive one, the non-recursive search is more complex and difficult to implement, but the stack size problem can be avoided.

Although a non-recursive function can realize the searching process, the efficiency of the search is also important. The reason is that when a break line network is large and complex, there may be so many possible paths between a pair of contour value points, that to go over all the possible paths and identify the shortest one will take too much time. In

Figure 5.14 Valley path searches: recursive (upper) and non-recursive (lower).

order to increase the search efficiency, the length of the possible path is dynamically calculated in the project. If the length of the possible path in the search has been longer than the previously searched path, and the destination point is still not reached, this possible path must be longer than the previous one and can be ignored. Therefore, the last point on the temporary list can be removed, the one before last will be taken as the current point, and the search can be continued from its other linked points. Once a point is reached at which the length of the possible path is longer than the previously found path, that point will be treated as the point where no further searching is necessary or possible. At these points, the search will step back one point to find another possibility. The difference is that at that point at which the length of the possible path is longer than a previously found path, the step back is not a natural but compulsory, which limits the search depth to a certain range. This measure will be significant when the initial possible path is very short, because the searching depth is restricted to a small range.

5.3 Data Testing

During the implementation, all the data used to test the programs were real contour line data in digital form collected by Intergraph TYDAC for software test. There were three sets of contour line data used in the project. One represents a hilly area in southern Ontario, another one represents coastal relief in the area of Nova Scotia, and the third one is contour lines of the northern Atlantic Ocean. To save time in testing the programs, all of the data were split into more than 10 small data sets. In the hilly area, many small hills are represented by self enclosed contour lines. These self enclosed contour lines make the valleys between them large and complex. All the cases discussed previously appear in that area. However, since the cases were considered during the implementation, the problems of triangle crossing contour lines and spurious horizontal triangles were correctly solved in

all of the data sets. The programs also work as efficiently as expected. For example, for a data set with 40,000 point in the area of southern Ontario, the programs take about 10 minutes to generate the Delaunay triangulation, 5 minutes to handle the problem of triangle crossing contour lines, 15 to 20 minutes to split horizontal triangles, and 40 minutes to interpolate elevations for all inserted points. Different data sets may consume more or less time, even though they have the same number of points, because the number of the triangles crossing contour lines and spurious horizontal triangles, and the complexity of the break line networks will not be exactly the same. The complexity of the break line networks will deeply influence the speed of interpolating elevations for the points in the networks. Generally speaking, with the same number of points, the data in hilly areas will require a longer time to process than the data in mountainous areas, because the break line networks in the data set in a mountainous area are normally smaller and simpler than those in hilly areas. Although more contour line segments might be crossed by triangles in mountainous areas, to process triangles crossing contour lines is much quicker than to process spurious horizontal triangles.

5.4 Summary

This chapter has discussed the implementation of AICTIN in the models of abstracting elevation sample points, generating Delaunay triangulation, splitting problem triangles by inserting supplementary points, and elevation interpolation for the inserted points. In this chapter, the Delaunay triangulation algorithm used in AICTIN has been introduced. A more practical and efficient method for splitting horizontal triangles has been discussed, as well as the method for searching valley paths. This chapter has also introduced the data used in the project, the result of the produced TIN, and discussed the computing time performance of AICTIN for a specific data set.

6 CONCLUSION

6.1 Summary and Conclusion

The research project successfully met its initial objectives: through the analyses of the relationships between relief, contour lines and contour based TIN, all problem triangles occurring in a contour based TIN can be automatically detected and eliminated, in order to provide a more accurate, better performing TIN structured DEM. The research was carried out mainly in three steps: conceptual design, algorithm design, and implementation and testing.

1) Conceptual design: conceptual design is the basis for the project's success. Based on the study and analysis of the previous approaches, a different approach - Analytical Improvement for Contour based TIN (AICTIN) -- was proposed. Through division of relief into basic topographic elements, and further abstraction of these elements from topographical to topological sense, the relations of each element to its associated contour line, and triangles were analyzed. Based on the relations, the triangles were classified into groups. The proposed solution -- insertion of points to split problem triangles, and elevation interpolation of the points -- was discussed.

2) Algorithm design: Algorithm design is an important connection between conceptual design and implementation. In this stage, the algorithms for splitting different groups of problem triangles and interpolating elevations for the inserted points were designed. Meanwhile, the importance of the processing sequence in splitting problem triangles and interpolating elevations was emphasized, and the processing sequence in AICTIN was discussed and designed.

2 of/de 2

PM-1 3 1/4" x 4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT

PRECISIONSM RESOLUTION TARGETS

3) Implementation and testing: AICTIN, as a complete approach to construct a contour based TIN, includes the abstraction of elevation points from contour lines; generation of Delaunay triangulation; detection and elimination of problem triangles by inserting points along break lines; and elevation interpolation for the inserted points. AICTIN was implemented with the C language on IBM compatible PCs, and tested with a number of real contour line data sets derived from topographic maps in different regions and at different scales. In the implementation, the Delaunay triangulation algorithm used in AICTIN was introduced, and some of the algorithms were further improved. The performance of AICTIN was also analyzed.

Based on the research performed so far, the following conclusions can be drawn:

1) DEM provides a powerful tool to understand and study landforms. Landform is one of the important factors which influences many aspects of people's life. In order to understand and study the landforms, it is necessary to represent the landforms accurately and vividly. But, since the earth surface is a three dimensional irregular surface, the representation of landforms is difficult for conventional methods. DEM, together with the associated software, provides the capability for people to obtain accurate topographic data, to display the relief in graphics, and to do various calculations on it, which are all significant for the understanding and study of landforms.

2) TIN is a good structure for DEMs. As a type of DEM structure, TIN has the following three main advantages: TIN is storage efficient by using fewer elevation sample points; TIN is accurate via the high accuracy of the elevation sample points; and TIN is also an optimal structure for conversion to other structures, such as grid and contour lines.

The triangulation algorithm for TIN is no longer a difficulty with the development of computational geometry.

3) *It is feasible to solve the problems occurring in contour based TIN by analyzing the relationships between relief, contour lines and the contour based TIN.* Since a variety of landforms can be represented by the basic topographic elements with different shapes and sizes, the relations of the elements to the associated contour lines and the triangles can be summarized. Through abstraction of the elements from topographical to topological sense and classification of the triangles according to their vertex elevations and edge properties, the relationships between relief, contour lines, and contour based TIN are clear. There, the combination of the problem triangles and the location of each triangle type in each element can be detected, and the process method for each type of triangle can be determined as well.

4) *Implementation and testing are important for examining the feasibility of the conceptual design, and for optimizing the algorithms.* Since implementation of an algorithm must consider the hardware resources of computers, such as the memory capacity, the stack size, and processing speed, it is an important test of the practical feasibility of the conceptual design, and also an opportunity to optimize the algorithms. In addition, because the earth surface is so complex and irregular that any approach dealing with terrain data can hardly be proven correct in all cases, testing with real data is necessary.

6.2 Suggestions for Further Development

As a research project, AICTIN has reached its objectives. However, a great deal of research effort is still required to improve AICTIN and contour based TIN in the following aspects.

1) Further testing of AICTIN with real contour line data in various geomorphologic regions. Although some preliminary tests were done, more tests are still necessary, because it is difficult to mathematically prove the completion of AICTIN. In addition, due to the complexity of landform, the contour lines are often interrupted. The interruption of the contour lines may lead to the irregular and unpredictable combination of different types of triangle. Therefore, it is significant to research how to detect problem triangles in a TIN generated from interrupted contour lines.

2) The storage efficiency of contour based TIN should be improved. The storage efficiency of TIN is one of its most important advantages to be applied in DEM. However, although the number of points on each contour line can be compressed to a minimum before constructing the TIN, all or part of some contour lines may not be necessary to adequately represent the earth's surface. Therefore, some of the elevation points in contour based TIN are not VIPs, and should be removed. These unnecessary parts of contour lines should be removed after the TIN is accomplished, because 1) these parts of contour lines are difficult to recognize before the TIN is constructed; and 2) the completion of the contour lines is important for the detection of problem triangles.

3) The examination and adjustment of contour based TIN with other features. AICTIN is designed to work on a surface which is completely represented with contour lines and scattered elevation points. The break lines of the area are generated from the

contour based TIN. However, these break lines are normally different from the real break lines, e.g. the generated break lines in valleys are probably not exactly the same as the rivers in those valleys. Research on the examination and adjustment of contour based TIN by using real break line information is suggested.

BIBLIOGRAPHY

Akima, H., (1978), "A Method of Bivariate Interpolation and Smooth Surface Fitting for irregularly Distributed Data Points", *ACM Transactions on Math. Software*, Vol. 4(2), pp. 148-59.

Akima, H., (1978), "Bivariate Interpolation and Smooth Surface Fitting for irregularly Distributed Data Points", *ACM Transactions on Math. Software*, Vol. 4(2), pp. 160-4.

Aronoff, S. (1989), *Geographic Information Systems: A Management Perspective*, WDL Publications, Ottawa, Canada.

Barben, F., et al, (1991), "Displaying Morphological and Lithological Maps: A numerically intensive computing and visualization application", *IBM J. Develop*, Vol. 35, No. 1/2, pp.78-81.

Birch, T. W., (1949), *Maps: Topographical and Statistical*, Oxford University Press, Amen House, London.

Brändli, M., (1991), "Überflächeninterpolation aus Höhenkurverdaten", *Geoprocessing Series 11*, Geographic Institute, University of Zurich, pp.57-67.

Brown, L. A., (1960), *Map Making: The Art That Became A Science*, Little Brawn and Company (Canada) Ltd.

Chen, Z., (1987), "Systematic Selection of Very Important Points (VIP) from Digital Terrain Model for Constructing Triangular Irregular Network", *Proceedings Auto Carto 8*, Baltimore, S, pp.50-6.

Christensen, A. H. J., (1987), "Fitting a Triangulation to Contour Lines", *Proceedings Auto-Carto 8*, Baltimore, S, pp.57-67.

Clarke, A. L., A. Gruen and J. C. Loon, (1982), "The Application of Contour Data for Generating High Fidelity Grid Digital Elevation Models", *Proceedings Auto Carto 5*, S. pp. 213-21.

- Coates, D. R.**, (1971), "Introduction to Environmental Geomorphology", *Environmental Geomorphology*, Publications in Geomorphology, State University of New York, Binghamton, New York.
- Correc, Y. and E. Chapuis**, (1987), "Fast computation of Delaunay triangulations", *Advances in Engineering Software*, Vol. 9(2), pp. 77-83.
- Daratech Survey**, (1989), *Computer Graphics World*, November, p. 22.
- Deveau, T. J.**, (1983), "Reducing the Number of Points in a Plane Curve Representation", *Proceedings Auto Carto 6*, pp. 152-60.
- Douglas, D. H. and T. K. Poicker** (1973), "Algorithms for the Reduction of the Number of Points Required to Represent a Digitized Line or its Caricature", *The Canadian Cartographer*, Vol. 8(2), pp. 112-22.
- Dwyer, R. A.**, (1987), "Faster divide-and conquer algorithm for constructing Delaunay triangulation", *Algorithmica*, vol. 2 (2), pp. 137-51.
- Finch, J. K.**, (1920), *Topographic Maps and Sketch Mapping*, John Wiley & Sons, Inc. New York.
- Finch, V. C. et al**, (1957), *Elements of Geography: Physical and Cultural*, McGraw-Hill Book Company, Inc., New York.
- Gold, C. M.**, (1977), "The Practical Generation and Use of Geographic Triangular Element Data Structure", *Harvard Papers on Geographic Information Systems 5 (Proceedings First International Advanced Study Symposium on Topological Data Structures for Geographic Information Systems, held in 1977)*
- Gold, C. M., T. D. Charters and J. Ramsden**, (1977), "Automated Contour Mapping Using Triangular Element Data Structures and an Interpolant over each Irregular Triangular Domain", *Computer Graphics*, Vol. 11, No. 2, S. pp. 170-5.
- Gold, C. M.**, (1989), "Spatial Adjacency - A General Approach", *Proceedings Auto Carto 9*, Baltimore, S. pp. 298-308.

Goodchild, M. F., (1990), "Geographic Information Systems and Cartography", *Cartography*, Vol. 19, No. 1, pp. 1-13.

Guan, J., and D. Liu, (1985), *Data Structure*, Higher Education Publications. Beijing, China (in Chinese).

Haggett, P. and R. J. Chorley (1969), *Network Analysis in Geography*, Edward Arnold Ltd., London.

Imhof, E., (1982), *Cartographic Relief Representation*, (English edited by H. J. Steward), Walter de Gruyter, Berlin.

Keates, J. S., (1982), *Understanding Maps*, John Wiley, New York.

Kendall, H. M., R. M. Glendinning, C. H. MacFadden, R. F. Logan and H. C. MacFadden, (1967), *Introduction to Geography*, Harcourt, Brace and Company, New York.

Kenzer, M. S., (1989), *Applied Geography: Issues, Questions, and Concerns*, Kluwer Academic Publishers, Boston.

Kumler, M. P., (1990), "A Quantitative Comparison of Regular and Irregular Digital Terrain Models", *Proceedings GIS/LIS '90*, Anaheim, California, S. pp. 255-63.

Lawrence, G. R. P., (1979), *Cartographic Methods*, Methuen, London.

Lobeck, A. K., (1939), *Geomorphology: An introduction to the study of landscapes*, McGraw-Hill, New York.

Luger, G. F., (1992), "Applying Artificial Intelligence: Expert Systems, Neural Network, and Object-Oriented Design", *Course Material*, Learning Tree International, Ottawa.

Maguire, D. J., (1991), "An Overview and Definition of GIS", in Maguire, D. J., M. D. Goodchild and D. W. Rhind, (eds.), Vol. 1, *Geographical Information Systems, Principles and Applications*, Longman Scientific and Technical, pp.9-20, New York.

Makarovic, Ir. B., (1977), "Digital Terrain Models -- A Constituent of Geo-Information Systems", *Harvard Papers on Geographic Information Systems 5 (Proceedings First International Advanced Study Symposium on Topological Data Structures for Geographic Information Systems, held in 1977)*.

Mayeda, W., (1972), *Graph Theory*, Wiley-Interscience, a division of John Wiley & Sons, Inc., New York.

McCullagh, M. J. and C. G. Ross, (1980), "Delaunay Triangulation of a Random Data Set for Isarithmic Mapping", *The Cartographic Journal*, Vol. 17, No. 2, S. pp. 93-9.

McCullagh, M. J., (1982), "Mini/micro display of surface mapping and analysis techniques", *Cartographica* 19(2), pp.136-44.

Muehrcke, P. C., (1986), *Map Use*, JP Publications, Madison, WI.

Patterson, D. W., (1990), *Introduction to Artificial Intelligence and Expert Systems*, Prentice-Hall, Inc., New Jersey.

Poicker, T. K., (1978), "Data Structure for Digital Terrain Models: Discussion and Comparison", *Harvard Papers on Geographic Information Systems 5 (Proceedings First International Advanced Study Symposium on Topological Data Structures for Geographic Information Systems, held in 1977)*.

Poicker, T. K., R. J. Fowler, J. J. Little and D. M. Mark, (1978), "The Triangulated Irregular Network", *Proceedings of the Digital Terrain Models (DTM) Symposium*, St. Louis, Miss. pp. 516-40.

Poicker, T. K., (1979), "Digital Terrain Models: An Overview", *Proceedings Auto Carto 4*, S. pp. 97-107.

Preparata, F. P., and M. I. Shamos, (1985), *Computational Geometry: an introduction*, Springer-Verlag, New York.

Raisz, E., (1948), *General Cartography*, McGraw-Hill, New York.

Robinson, A. R., et al., (1984), *Elements of Cartography (5th edition)*, John Wiley & Sons Inc., New York.

Scarlato, L. L., (1989), "A compact Terrain Model based on Critical Topographical Features", *Proceedings Auto-Carto 9*, Baltimore, S. pp.146-55.

Schutzer, D., (1987), *Artificial Intelligence -- An Applications-oriented Approach*, Van Nostrand Reinhold Company, New York.

Shiryaev E. E. (1987), *Computers and the representation of geographical data*, John Wiley & Sons, New York.

Taylor, D. R. F., (1991), *Geographic Information Systems, The Microcomputer and Modern Cartography, Modern Cartography*, Vol. 1, Pergamon Press, New York.

Theobald, D. M. and M. F. Goodchild, (1990), "Artifacts of TIN-Based Surface Flow Modeling", *Proceedings GIS/LIS '90*, Anaheim, California, S. pp. 955-67.

Weibel, R. and M. Heller, (1990), "A Framework for Digital Terrain Modeling", *Proceedings Fourth International Symposium on Spatial Data Handling*, Zurich, S. pp. 291-29.

Weibel, R. and M. Heller, (1991), "Digital Terrain Modeling", In Maguire D. J., M. F. Goodchild and D. W. Rhind, (eds.), Vol. 1, *Geographical Information Systems, Principles and Applications*, Longman Scientific and Technical Ltd., New York, pp.269-97.

Yang, J., L. Wang, X. Tang, and Z. Wang, (1990), "Development and Application of MIGIS --- The kernel system for Micro Geographic Information System", *Proceedings of 11th Asia Remote Sensing Conference*, Guangzhou, China.

Zhu, G., and Yin, G. (1982), *Compilation of General Maps*, Publications of Surveying and Mapping, Beijing, China (in Chinese).

END

3 | 0 - 0 5 - 9 5

FIN